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Testing Fish Deterrents for Use Under-Ice in the Mackenzie Delta Area and Potential Impacts

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TESTING FISH DETERRENTS FOR USE UNDER-ICE IN THE MACKENZIE DELTA AREA

A study conducted by

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Abstract

Non-contact deterrent technologies, both acoustic and visual, are often used in aquatic settings in lieu of physical barriers to address the threat posed to fish by industrial operations. The goal of this study was to determine the efficacy of portable, temporary deterrents as a means of excluding fish from areas of detonation activities associated with seismic exploration in Mackenzie Delta lakes. In October 2003, trials were conducted at Dolomite (Airport) Lake near Inuvik, Northwest Territories using lake whitefish (*Coregonus clupeaformis*), broad whitefish (*Coregonus nasus*), inconnu (*Stenodus leuichthys*), lake trout (*Salvelinus namaycush*), and northern pike (*Esox lucius*). Groups of fish were equipped with orally inserted acoustic tags, placed in a 1000 m3 experimental net pen and monitored using a fish tracking system that produced a detailed swimming pattern, thereby revealing behavioural responses. A multi-frequency sound projector and a strobe light were tested as deterrents. Further consideration of the latter as a deterrent in northern lakes is not recommended on account of the low light propagation encountered in lake water. Although the study did not identify an overall satisfactory deterrent, sufficient indications of response were observed in the acoustic source trials to recommend the testing of a louder sound projector capable of emitting a tonally modulated sound pattern at frequencies from about 100 Hz to a few kHz.

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Executive Summary

Protection of fish through mitigation measures, as directed by regulatory agencies, is an important aspect of all in-water industrial activities. Non-contact deterrent technologies are used when fish cannot be excluded from a dangerous area of work through the use of physical barriers. Underwater noise and strobe lights are the most commonly used non-contact deterrents in lakes and oceans to keep fish away from permanent installations (e.g. water intake structures). Studies show that most technologies tend to discourage only certain species of fish and may in fact have an attractant effect on others. The development of a more effective method is required to deter fish from areas of transient sub-bottom blasting activities associated with seismic exploration in northern lakes.

The purpose of this study was to determine the usefulness of portable, temporary deterrents – both acoustic and visual – on various locally significant and economically important northern freshwater fish species. Dolomite Lake (a.k.a. Airport Lake) near Inuvik, Northwest Territories, was chosen as the test site due to its accessible location and the presence of the relevant species. Experimental work was conducted in October 2003 just prior to freeze-up to closely mimic winter conditions, the season during which seismic work is carried out beneath the frozen surface of lakes.

Lake whitefish (*Coregonus clupeaformis*), broad whitefish (*Coregonus nasus*), inconnu (*Stenodus leuichthys*), lake trout (*Salvelinus namaycush*), and northern pike (*Esox lucius*), all native to the region, were selected for study, as they are potentially susceptible to winter seismic activity because of their abundance and overwintering habits. While fyke nets were the preferred method of capture, early ice-up prevented their use. As a result fish were captured using attended gill net sets and angling. Each fish was tagged with an internal gastric acoustic tag (HTI 795E) to record the individual fish swimming behaviours by means of ultrasonic tracking. The insertion process is relatively non-stressful and anaesthesia is not required. Three mixed test groups were placed sequentially in a 1000 m3 experimental net pen. Following each trial the fish were dip-netted from the vertically gathered net pen, the acoustic tags were removed by pulling on a retrieval wire that extended through the mouth, and the fish were released into the open lake.

The 10 m x 10 m x 10 m experimental net pen was open at the surface, with air filled floats attached to its top corners and Styrofoam blocks to enhance floatation and prevent escapes. It was secured and tensioned into a square by means of anchor lines secured to cement blocks on the lake floor. Riser lines were also attached to the blocks and held taut by floats; two sound level monitoring hydrophones and four fish tracking hydrophones were placed on these lines to record acoustic deterrent levels and document fish behaviour. The acoustic deterrent, a multi-frequency sound projector, was deployed at various testing stations along a straight line at distances of 5, 15, 30 and 45 m from a side of the pen. The visual deterrent, an adjustable-rate strobe light, was only tested adjacent to the side of the net pen as the light flashes were barely discernible even at night beyond a few metres in the lake water.

Strobe lights have been reported to be effective as fish deterrents at rates of 200 to 500 flashes per minute; this study used strobe rates of four and eight pulses per second (240 and 480 flashes per minute) in separate tests. The acoustic source (a commercial Broadband Acoustic Transmission System – BATS) was set up to produce six types of modulated tonal patterns at frequencies between 50 Hz and 3 kHz that were individually tested for effectiveness as deterrents.

The fish tracking system used (HTI Model 291 and associated software) analyzed the "pings" (ultrasonic pulses) produced by the fish tags and received by the tracking hydrophones. Graphs were produced to show a detailed representation of each fish's swimming behaviour and possible reaction to the different stimuli. Indications of which stimuli produced a behavioural response were obtained by cross-referencing the motion patterns with precisely timed activation intervals of the deterrent.

Of the 23 fish captured and tagged, 20 were successfully studied during the three sets of trials. A large amount of detailed path information was generated, documenting characteristic swimming behaviours for each species. Swimming path analysis also showed differences between day and night time hours.

Although the results indicate that some avoidance response did occur for certain visual and acoustic stimuli in given species, the study did not identify an effective general deterrent among the methods that were tested. Neither the sound nor light sources caused a significant number of the fish in the study to move away from the stimulus to the outer reaches of the pen. On the basis of this study further consideration of strobe lights as fish deterrents in the Mackenzie Delta lakes is not recommended because of the limited light propagation due to turbidity (suspended matter) and the consequent need for very high power output, especially in an omni-directional light source. The results support the recommendation that further research be focused on the use of a louder sound projector generating tonally modulated sound patterns at frequencies from about 100 Hz to a few kHz.

Project field team

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Résumé

La protection des poissons par la mise en œuvre des mesures d'atténuation des impacts, telles qu'exigées par les organismes de réglementation, est un aspect important de toutes les activités industrielles qui touchent l'eau. Des techniques d'éloignement à distance sont utilisées lorsque le poisson ne peut pas être exclu d'une zone de travail dangereuse à l'aide de barrières physiques. Les signaux soniques subaquatiques et les flashs de lumière stroboscopiques sont les deux méthodes les plus couramment utilisées pour éloigner sans les toucher les poissons des installations permanentes situées dans les lacs et en mer (p. ex. ouvrages de prise d'eau). Des études ont montré que la plupart des techniques ont tendances à ne décourager que certaines espèces de poissons et peuvent en fait agir comme attracteurs pour d'autres. Il est donc nécessaire de mettre au point une méthode plus efficace qui permettra d'éloigner les poissons des zones où sont effectués des minages du plancher des lacs, en profondeur, dans le cadre de l'exploration sismique dans le Nord.

L'objet de cette étude était de déterminer l'efficacité de systèmes portables et temporaires – acoustiques et visuels – pour diverses espèces de poissons d'eau douce du Nord ayant une importance locale ou économique. Le lac Dolomite (aussi appelé lac Airport), près d'Inuvik, dans les Territoires du Nord-Ouest, a été choisi comme site d'essai à cause de sa facilité d'accès et de la présence des espèces pertinentes. Des expériences ont été menées en octobre 2003, juste avant la prise de la glace, pour se trouver aussi proche que possible des conditions hivernales durant lesquelles les travaux sismiques sont effectués sous la surface gelée des lacs.

Le Grand corégone (*Coregonus clupeaformis*), Le Corégone tschir (*Coregonus nasus*), l'Inconnu (*Stenodus leuichthys*), la Truite de lac (*Salvelinus namaycush*) et le Grand brochet (*Esox lucius*), tous indigènes de la région, ont été choisis pour l'étude puisqu'ils sont tous potentiellement sensibles aux activités hivernales d'exploration sismique à cause de leur abondance et de leurs habitudes d'hivernage. Les chercheurs auraient préféré utiliser le verveux pour capturer les poissons mais la prise précoce des glaces les en a empêchés. Les poissons ont donc été capturés à l'aide de filets maillants tendus sous surveillance et à la ligne. Les chercheurs ont inséré dans l'estomac des poissons un émetteur acoustique gastrique (HTI 795E) permettant d'enregistrer le comportement natatoire individuel de chaque poisson à l'aide de signaux ultrason. L'insertion de l'appareil n'engendre pratiquement aucun stress chez le poisson et aucune anesthésie n'est nécessaire. Trois groupes de poissons mixtes ont été placés séquentiellement dans un parc en filet expérimental de 1000 m^3. À l'issu de chaque essai, les poissons ont été re-capturés à l'épuisette à l'intérieur du parc en filet rassemblé verticalement, les émetteurs ont été retirés en tirant sur un câble qui dépassait de la bouche des poissons puis ces derniers ont été relâchés dans le lac.

Le parc en filet expérimental de 10 m x 10 m x 10 m était ouvert en surface, avec des flotteurs remplis d'air attachés à ses coins et des blocs en polystyrène expansé pour améliorer la flottaison et éviter les échappées. Le filet était attaché et tendu suivant un carré à l'aide de lignes d'amarrage attachées à des blocs de béton posés au fond du lac. Des lignes montantes étaient également attachées aux blocs et tenues tendues par des

flotteurs; deux hydrophones d'enregistrement du niveau sonore et quatre hydrophones pour le suivi des poissons étaient placés sur ces lignes pour enregistrer le niveau acoustique émis pour éloigner les poissons et le comportement de ces derniers. L'émetteur acoustique, un projecteur sonore multi-fréquences, a été installé le long d'une ligne droite, à 5, 15, 30 et 45 m du côté du parc. L'émetteur de lumière, un stroboscope à fréquence ajustable, n'a été essayé que tout contre le côté du parc car les flashs devenait très rapidement indiscernables, même la nuit, lorsque le stroboscope était placé au-delà de quelques mètre dans le lac.

Des études ont montré que les stroboscopes réglés sur des fréquences allant de 200 à 500 flashes par minute étaient efficaces pour éloigner les poissons; dans cette étude, nous avons utilisé deux fréquences, quatre et huit flashs par seconde (240 et 480 flashes par minute) lors d'essais séparés. La source acoustique (un système de transmission acoustique à large bande – BATS) a été réglée pour produire six types de signaux modulés, à des fréquences variant entre 50 Hz et 3 kHz, dont l'efficacité a été testée individuellement.

Le système de suivi des poissons (HTI Model 291 et le logiciel connexe) a permis d'analyser les « pings » (pulses ultrasoniques) produits par les émetteurs placés dans l'estomac des poissons et reçus par les hydrophones de suivi. Des graphiques ont été construits pour représenter de manière détaillée le comportement natatoire de chaque poisson en fonction des différents stimuli. Les chercheurs pouvaient déterminer quelles réponses comportementales suivaient tel ou tel stimulus par simple corrélation temporelle entre le stimulus et la réponse.

Parmi les 23 poissons capturés et marqués, 20 ont pu être étudiés durant les trois ensembles d'essais. Une grande quantité de données décrivant en détail la nage des poissons ont été générées pour chaque espèce. L'analyse des trajectoires a également permis de mettre en évidence des différences entre les réponses diurnes et les réponses nocturnes des poissons aux stimuli.

Bien que les résultent montrent que les représentants de certaines espèces se sont quelque peu éloignés après avoir perçu certains stimuli visuels et acoustiques, l'étude n'a pas permis de mettre en évidence une méthode d'éloignement générale efficace parmi toutes celles testées. Ni les signaux sonores ni les flashes lumineux n'ont provoqué l'éloignement d'un nombre important de poissons vers la périphérie du parc. Compte tenu de ces résultats, il n'est pas recommandé d'envisager plus avant l'utilisation des stroboscopes pour éloigner les poissons dans les lacs du delta du Mackenzie, la propagation de la lumière dans ces lacs étant de plus très limitée en raison de la turbidité élevée des eaux (matières en suspension) et nécessitant donc l'emploi d'appareil à très haute puissance, en particulier pour les sources lumineuses omnidirectionnelles. Il est par contre recommandé de poursuivre les travaux de recherche sur l'utilisation d'un projecteur sonore plus puissant capable de générer des pulses modulés en fréquences entre 100 Hz et quelques kHz.

Introduction

The importance of protecting the fish population from collateral injury or mortality caused by industrial operations is clearly recognized by regulatory agencies, and significant effort is expended in implementing mitigation measures in a number of contexts. Where it is not possible to lessen the intrinsic threat posed by an operation, or to exclude from access the danger zone by means of physical barriers, non-contact deterrent technologies have been used in a number of instances. Perhaps the most well known examples are found in the electric power generation industry, where the entrainment of fish into intakes of turbines or other high flow rate conduits can cause huge losses in their population. Permanent installations of deterrents based on acoustic, visual or electrical stimuli have been widely documented (Turnpenny *et al.* 1998, Therrien and Bourgeois 2000) and their efficacy studied by a variety of methods. One recurrent finding is that any specific implementation of a deterrent technology tends to be effective on some species but not on others, in some cases even achieving an attractive effect. In the case of acoustic deterrents the frequency of the sound is the major parameter determining the effectiveness on given species, while for visual deterrents the pulsing rate of a strobe light can similarly affect its influence. The use of fish deterrents as blast damage mitigation devices in non-permanent or mobile installations is less widespread; examples can be found in the underwater demolition industry where a temporary deterrent system may be set up at a blasting site to exclude fish from the area. Unlike in permanent installations, the issue of long-term adaptation is not of significant importance in these systems as the fish are only exposed to the stimulus for occasional and usually brief periods of time.

The study presented here had the goal of assessing the effectiveness of a selection of portable, temporary deterrent technologies on different fish species found in the Mackenzie Delta lakes in the Northwest Territories. Any deterrent technology to be considered would have to cause no harmful effects on either the fish or other aquatic life forms. The objectives of the project were to compare the range of influence, the consistency of effect on a given species and the breadth of effectiveness across different species of various deterrents, and hopefully identify one or more technologies that would be useful in excluding most fish from the immediate proximity of explosions set off in the sediment beneath water bodies for seismic exploration. The use of explosives for this purpose has been the subject of controversy, especially in the wake of monitoring programs conducted during the winter of 2001/2002. These revealed that even with setback distances (depths of burial of the charge) as large as five times those outlined in the official Fisheries and Oceans guidelines a significant number of shots exceeded the safe threshold of 100 kPa instantaneous pressure change in the water column just above the shot point (Cott *et al.* 2003). Given this apparent unpredictability in the efficacy of charge setback as a mitigation measure, the additional safeguard offered by fish deterrents could provide, if proven reliable, greater confidence in the viability of explosives as environmentally acceptable seismic sources for use beneath water bodies.

Overview of approach

In planning an experimental methodology that would be optimally suited for this work, we examined the fish response monitoring methods adopted in prior published studies to determine their applicability to the current situation. Our review pointed to the need for an approach different from the majority of other related projects, which were concerned primarily with fixed deterrent installations such as those located around turbine intakes at hydroelectric dams. When evaluating these deterrents the interest is primarily in determining at a bulk level how effective they are in excluding fish from a water volume; relatively little importance is given to differentiating and quantifying the effect of a deterrent on individual species. Furthermore the fish population density in the water body under study is generally substantial and can be assumed to be in a statistical "steady state" condition. Under these circumstances the approach of using volume echo-sounding techniques such as split beam and multi-beam sonar to build a distribution map is reasonable and often adopted (e.g. Maiolie *et al.* 1999, Johnson *et al.* 2003). Only a few of these studies (e.g. Steig and Timko 2000) have used ultrasonic telemetry to follow the path of individual tagged animals.

For the present project, on the other hand, the case against acoustic volume sampling and in favour of ultrasonic tracking was deemed to be strong because of the conditions and the requirements of the study. Firstly, the density of the fish population in the target lake at the time of the study was not expected to be high enough to allow a meaningful distribution map to be built through a sequential echo-sounding process, as the motion of individual fish in a sparse population would undermine the sampling process; moreover the assumption of a "steady state" condition following the activation of the deterrent stimulus would not apply because of the transient and short-lived nature of the latter (in an operational scenario the deterrent device would likely be switched on at most a few minutes ahead of the shot and deactivated immediately after). Secondly, the value of the study would depend greatly on the detailed monitoring of the reaction of the fish to the deterrent signal, and ultrasonic tracking would provide a time resolved history of the individual evasive responses for several individuals at once. Thirdly, the various species of interest are represented in different concentrations in the fish population in the wild, and any study performed by acoustic volume sampling would not allow a balanced monitoring of the response of each species even if it were possible to distinguish between them from their echo returns. In ultrasonic tracking of tagged animals, individual fish are uniquely identified by their transmitted tag code and even in a mixed group the individuals from each species would be readily followed. We did, however, recognize the fact that the behaviour of a mixed population in a confined area would risk being influenced by interaction or avoidance between individuals of different species. We decided therefore on an experimental methodology in which:

- The motion response of fish to various deterrent stimuli, of both acoustic and visual types, would be studied in detail through concurrent three-dimensional ultrasonic tracking of several individuals exposed to the stimuli.
- Each trial group would be composed preferably of animals of a single species, and if a mixed group had to be tested no species would be combined that had a known predator prey relationship.
- The individuals under active study would be bounded in their displacement by a net pen suitable to confine them to an easily monitored volume but large enough not to impede their initial response to a stimulus, as established from professional

expertise with installations of a similar nature (Robert Bocking, LGL, personal communication, August 2003).

- The deterrent devices would be positioned at various pre-determined offsets from one side of the pen to study the response of the individuals at exposure distances greater than the dimensions of the pen itself.

The realities of field work under pressing time and weather conditions, as well as a lower capture and retention success than anticipated for some species, did force us to abandon the species isolation rule on the last day of trials and combine individuals of various kinds into a single experimental group. Even so, the tracking records did not reveal a significant level of behaviour alteration that could be attributable to the co-existence of species.

Staging of study and fish handling methodology

Location and timing

Fish behaviour varies with seasonal changes in lakes. Specifically, water temperature can significantly affect fish behaviour. Lake trout (*Salvelinus namaycush*)—for example—actively seek out cool, hypolimnetic water during summer months but then move into shallower waters to spawn in the fall when the lake temperature cools (Scott and Crossman 1973). Since explosive based seismic exploration activities in the Northwest Territories take place during winter when lake surfaces are frozen, it was critical that the fish deterrent studies take place during a period when the test location would be at or near winter conditions. The reaction of fish to a deterrent could, in effect, be markedly different when the animal is in warmer summer waters than when it is in near freezing temperatures. Logistical and budgetary considerations led to conducting these studies in the fall just prior to freeze-up, a period when any temperature related behaviour of the subjects would closely approach winter conditions without being associated with the complexity of deploying and operating equipment under the ice. Dolomite or Airport Lake (N 68°17′ W 133°30′) located near Inuvik, Northwest Territories was selected as the test location since all relevant species were known to reside in that water body and its tributary streams, and the proximity of the lake to an airport and town, with good road connections, simplified the staging and support logistics. This lake also has a suitable bathymetry, with bottom depth exceeding 10 m near shore at conveniently accessible locations, and is known for the comparative clarity of its water which would assist in evaluating a visual deterrent. The opportunity window for the study was set to early to mid October based on historical records of freeze-up on that lake.

In the weeks leading up to the target period, widely varying weather conditions in Inuvik ranging from spells of unseasonable warmth to a blizzard made it very difficult to estimate when the icing might begin. Other lakes in the area were either frozen or in the process of freezing by the beginning of October, although Airport Lake was traditionally known to remain open for a longer period. Meanwhile, unexpected delays in the delivery of a specialized sound source to be used as test deterrent prevented an earlier staging of the trials. The field work was carried out from 7 to 17 October 2003, with set-up and preparatory tasks running from the 7th to the 13th and actual trials from the 14th to the 16th. Air temperatures during this period ranged from 4°C to -13°C, while surface water temperature measured near the staging area declined from 3°C to 1°C. Approximately one third of the lake in shallower zones was ice covered by 15 October, and by the start of tear-down on the morning of the 17th a thin ice layer had nearly encroached on the main net pen some 50 m off the shoreline in over 10 m of water depth.

Species investigated

The study was conducted on locally relevant, traditionally and economically important northern fish species that, by their general abundance and over-wintering habits, are potentially susceptible to winter seismic activity. Fish species investigated consisted of: lake whitefish (*Coregonus clupeaformis*), broad whitefish (*Coregonus nasus*), inconnu (*Stenodus leuichthys*), lake trout (*Salvelinus namaycush*), and northern pike (*Esox lucius*). Their characteristics and habits are well documented in the literature (e.g. Scott and Crossman 1973); a brief summary of relevant information from that source is provided below.

Lake whitefish is of the family Coregonedae. It has an average length of 40 cm. Spawning occurs in the fall before freeze-up, in shallow water at depths of less than 8 m. In extreme northern areas, spawning may occur only every second or third year. Aquatic insect larvae, mollusks, and amphipods are primary food items. Lake trout, northern pike, and burbot are major predators of whitefish. The lake whitefish has the widest distribution of all whitefish species in the Northwest Territories and is the most common commercially sold fish found in the region.

Broad whitefish is another member of the family Coregonedae. Its distribution includes both the fresh and brackish waters of the arctic drainages of northwestern North America and northern Eurasia, south to approximately the 60th parallel. In the lower Mackenzie drainage it is believed to grow larger than lake whitefish and has an average total length of 46 cm. Broad whitefish reside more frequently in rivers than lakes. Broadcast spawning occurs in rivers over gravel substrate. Broad whitefish are bottom feeders, feeding mainly on molluscs and aquatic insects. In the northwest, broad whitefish are usually taken by gillnet for local comsumption only, for use as both human and dog food.

Inconnu is also of the family Coregonedae. Inconnu is larger than other whitefish species and is usually 45–75 cm in length. Spawning occurs in late summer or early autumn in rivers. In coastal areas, the inconnu is an anadromous species, ascending freshwater streams to spawn. In inland lakes, they spawn in tributaries to lakes and overwinter in lakes. “Coney” (as they are locally known) are predatory fish that are usually caught in gillnets in the fall during the downstream run, and also by angling or by “jiggling” (jigging with a relatively short line through the ice).

Lake trout average 40–50 cm in length but can grow to over 22 kg. They are a fall spawner at depths ranging from 1 m to 20 m over large boulder or rubble bottom. After spawning, they disperse freely throughout the lake at various depths and remain so throughout the winter. Lake trout prey on a broad range of organisms including crustaceans, insects, fish and even small mammals. Lake trout is highly prized both as a game fish and as a subsistence and commercial species. Ice fishing for lake trout is very popular. One of the most widespread fish in the Northwest Territories, the lake trout is found throughout the Mackenzie, Thelon, Back and Coppermine drainage systems.

Northern pike is a large (45–75 cm), spring spawning freshwater fish of the Esocidae family. They are voracious predators that will eat any living animal available to them, up to one half the size of the pike itself. Northern pike are present in large numbers across the Mackenzie Delta; they are relatively easy to catch with hook and line and are an important sport fish in winter fisheries through the ice. They are also widely caught by gill net and used extensively for dog food.

Fish capture and handling

Passive capture of fish using fyke nets was the preferred capture method, backed up by attended gill net sets and angling. Suitable locations for fyke-netting with 100 m lead assembly occurred along the NW shoreline of Airport Lake. Unfortunately, this shallow (<1 m) and gentle sloping shoreline was the first area to ice-up on 8 October 2003, precluding the utilization of fyke traps. Angling success was reasonable at the start of the field work period, but angling capture rates declined steadily as water temperatures decreased to 1°C. Accordingly, attended gill net sets consisting of four 15.2 m panels (2.5 cm, 5.0 cm, 7.5 cm, 10.0 cm mesh) became the primary capture method.

Figure 1: Specimen of acoustically tagged lake whitefish showing the retrieval wire extending out of the mouth and kinked backward not to affect normal activities. The inset shows an HTI 795E ultrasonic tag with size reference.

Upon capture, individual fish were placed in water filled 151 litre capacity totes for boat transport to one of two holding pens, each measuring 3 m x 3 m x 2 m deep and set up in a small embayment area of Airport Lake. This area was several hundred metres away from the main staging set-up, ensuring that fish being held prior to being involved in trials would not be pre-exposed to perceptible acoustic or visual stimuli from deterrent sources used on other groups. Fish were allowed to acclimatize in the holding pens for 12 to 48 hours prior to being tagged. The gastrical tagging process involved holding the fish in a water-filled trough while an HTI 795E acoustic tag measuring 0.68 cm diameter by 2.1 cm in length and equipped with a teflon-coated retrieval wire (Figure 1) was inserted down its throat with a hollow plastic applicator to a point just past the sphincter. This procedure does not induce excessive stress in the subject and does not require the use of anaesthetics like surgical implantation; anaesthesia would have been counter-productive to the study as it prolongs the recovery period of the fish and can influence behaviour.

Tagged fish were initially held in a small-meshed (aperture = 0.75 cm) one cubic metre holding pen and monitored for health and tag retention for at least an hour. However, it soon became apparent that tagged fish were more vigorous and less stressed when placed directly into the original 18 m^3 holding/recovery pen where they naturally sought out security with depth. Fish swimming performance and behaviour appeared unaffected. A low density of penned fish was believed to be an important factor in controlling stress.

Deterrent trials were conducted on three groups of test fish. The first test group consisted of eight lake whitefish (fork length range: 40.5–45 cm), the second group of seven northern pike (fork length range: 51–59 cm). The third group was made up of three broad whitefish (fork length range: 43–49 cm), two inconnu (fork length range: 57–74 cm) and two lake trout (fork length range: 63–64 cm). The lake whitefish were allowed to acclimatize overnight in the 1000 m^3 experimental net pen as originally proposed before the deterrent trials were conducted on 14 October. However, the acclimatization period for the two subsequent trial groups (tested on the 15th and 16th respectively) was shortened to two hours due to deteriorating weather conditions and the justified concern that the experimental net might become ice bound prior to completion of the desired set of tests. At the end of each group's deterrent trials, the floor of the experimental pen was raised by gathering up the sides so that the fish could be confined at one shallow end and dip-netted; the acoustic tags were removed from their throats by pulling on a retrieval wire before the fish were released into the open lake.

Experimental set-up

Equipment layout

The projective rendering in Figure 2 shows the installation layout of the containment pen and the various monitoring sensors deployed around it to measure the acoustic levels to which fish were exposed and track the motion of individual animals. The net pen was a 10 m x 10 m x 10 m cube of small 5-cm knotless stretch mesh, open at the surface, with air filled floats attached to its top corners. Flotation was enhanced using styrofoam blocks around the upper edges to prevent the possibility of fish escaping over semi-submerged borders, due to ice build-up on the exposed netting. The net was tensioned into a square plan by means of guy lines running from the corner floats to four heavy cement anchor blocks dropped to the lake bottom in an arrangement as close as possible to a square of 30 m side. The drop locations of the anchor blocks were determined and surveyed through laser range-finder fixes to points on the shoreline and to the locations of already deployed blocks marked by styrofoam buoys on taut riser lines. The riser lines also provided mounting support for two sound level monitoring hydrophones at 5 m depth and four fish tracking hydrophones, two of which were lowered close to the 10 m depth of the pen bottom (1 to 2 m off the lake floor) and two deployed 1 m below the surface on diagonally opposite corners. The relative locations of all these elements are shown to scale in the layout diagram.

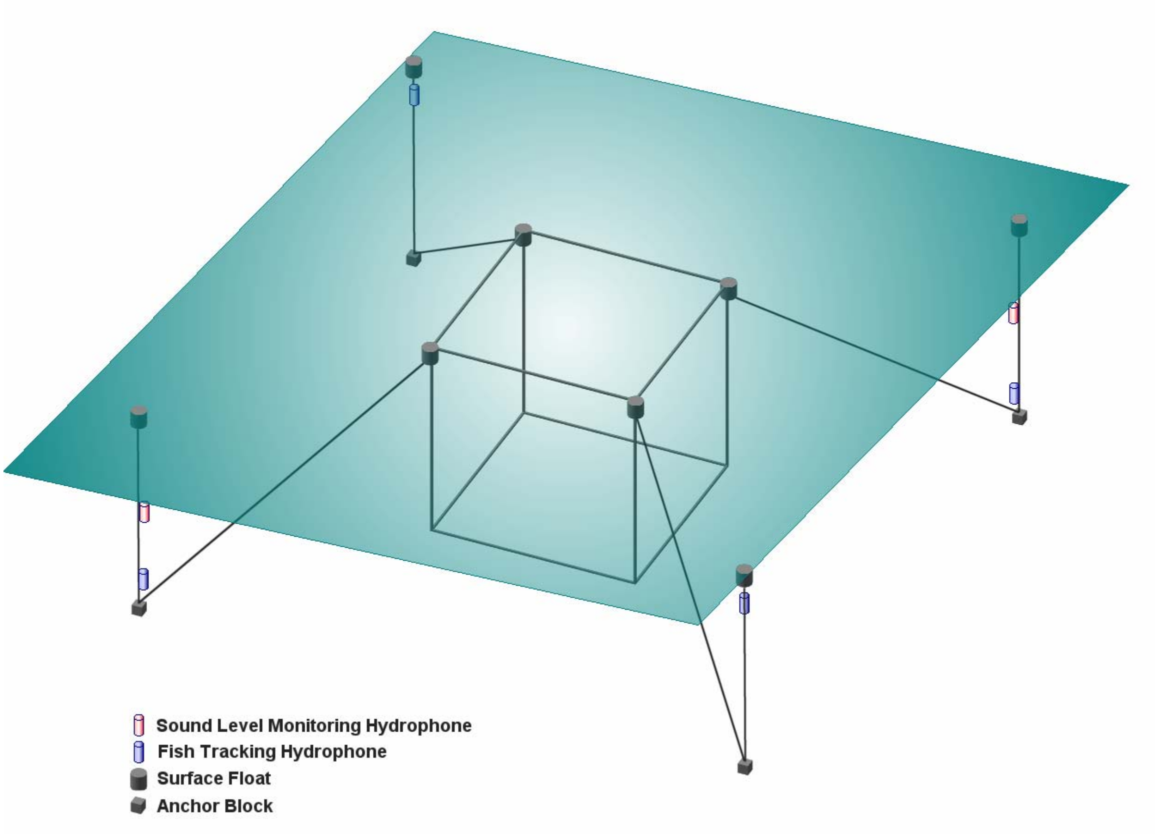

Figure 2: Layout of containment pen and monitoring sensors.

The deployment offsets for the acoustic deterrent stimulus source were pre-measured by laser rangefinder and marked by dropping rock-filled canvas anchor bags to which styrofoam surface floats were attached on taut riser lines. The anchor bags allowed the riser lines and floats to be used as tie-up points for a small inflatable boat from which the source would be lowered to a standardized depth of 5 m prior to activation.

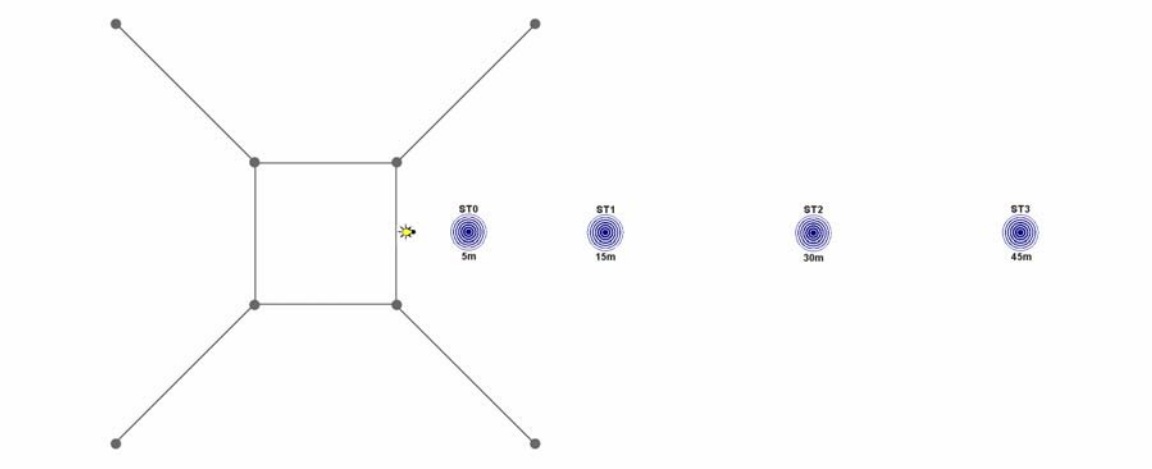

Figure 3: Deployment locations for deterrent sources.

Figure 3 shows in plan view the deterrent deployment locations relative to the net pen and its anchor points, which also mark the position of the monitoring sensors. For positional cross-referencing with Figure 2, note that the two sound level monitoring hydrophones are at the upper right and lower left anchor points in the plan view. The deployment points were aligned along a centreline of the pen in an orientation roughly parallel to the shore, which lay some 50 m off the lower edge of the pen in the plan view. The flashbulb symbol denotes the single deployment point for the visual deterrent (strobe) source, which was placed as close as possible to a side of the net pen since it was found in preliminary tests that the light signal would essentially die off within 10 m in the lake water. The four radiating wave symbols marked ST0 to ST3 denote the deployment stations for the acoustic source at 5, 15, 30 and 45 m from the nearest side of the pen respectively. The propagation distances between the acoustic source and the sound monitoring hydrophones were precisely surveyed above water by laser rangefinder measurements from the deployment stations to the floats on the riser lines supporting the hydrophones. The deployment offsets were originally selected to provide a range of distances for deterrent testing commensurate with the fish exclusion radii that ideally one would want to achieve, namely some tens of metres from the seismic charge location; this was based on the assumption that fish response to the deterrent would be significantly greater than was actually observed. In effect the deployment station ST0 at 5 m was only introduced on the second day of actual trials when preliminarily processed tracking data revealed no apparent response to acoustic stimuli projected from stations ST1 to ST3, and acoustic monitoring had indicated that sound pressure levels even at such close proximity would be well below the minimum hearing injury threshold for fish of 180 dB re µPa (Turnpenny *et al.* 1998). An ensemble photograph of the equipment layout as seen from the shore of the lake near the instrumentation site is shown in Figure 4. The pair of floats at the left edge of the image and their counterparts on the opposite side of the net pen maintained tension on the riser lines from the anchor blocks, to which the hydrophones were attached. The four smaller floats aligned along the horizontal centreline in the right half of the image marked the deterrent deployment stations ST0 through ST3.

Figure 4: Ensemble view of experimental layout in Airport Lake.

Sound level monitoring instrumentation

Measurements of sound levels from the acoustic source at locations in the proximity of the net pen were performed using two Reson TC4043 pre-amplified hydrophones, with a calibrated nominal sensitivity of 201 dB re V/µPa ± 1 dB. These sensors were installed, along with fish tracking hydrophones below them, on two diagonally opposite riser lines from the anchor blocks as per Figure 2. Figure 5 shows a TC4043 and an HTI Model 590 fish tracking hydrophone with the mounting hardware used to deploy them. The hydrophones were taped to tubular guides made of PVC pipe, which allowed them to be threaded on a line and lowered along it. Each TC4043 was held at a depth of 5 m by suspending it from the surface float above it on a measured length of nylon cord. The cord extended further downward to support the fish tracking hydrophone, whose weight tensioned the assembly and held it fast. Signals from the TC4043s were transmitted to shore via 50 Ω shielded coax cables laid on the lake bottom, and fed into two Ithaco 541M selectable gain amplifiers (-10 dB to +80 dB in 1 dB steps). The amplifiers' built-in high pass filters were set to a cut-off frequency of 10 Hz to eliminate very low frequency noise without attenuating even the lowest ranges of the sounds being monitored. The amplified signals from the two hydrophones were recorded to PC-compatible Microdrive digital media using a single Marantz PMD690 audio recorder operating in stereo mode. Customary precautions were taken to ensure that audio recordings would be as free as possible of electrical noise background; in particular, a petrol-powered generator that provided recharging AC power to the audio recorder, notebook PC and ancillary instrumentation (oscilloscope etc.) was shut down during audio monitoring sessions and all equipment run from batteries alone.

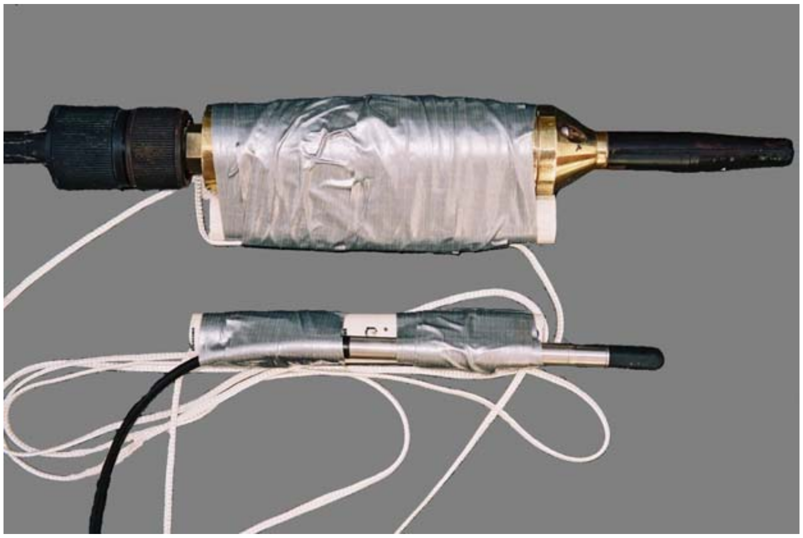

Figure 5: HTI Model 590 ultrasonic tracking hydrophone (above) and Reson TC4043 acoustic monitoring hydrophone, fastened to PVC tubular guides and suspension cord.

Fish tracking system

An HTI Model 291 acoustic tracking system was used to achieve a highly accurate monitoring of response and rigorous documentation of fish behaviour. Its operation is based on the detection of ultrasonic pulses (300 kHz carrier) from miniaturized acoustic transmitters inserted non-surgically in the fish under study. Multiple hydrophones receive the individual pulses, pre-amplify them and send them to a processing unit. Through signal processing techniques the unit improves the signal to noise ratio of the pulses and establishes their exact time of arrival at each hydrophone, from which the position of the tag is computed. This is achieved even if multiple tags are transmitting in proximity of each other, as each of them "pings" at a unique programmed repetition rate (in the order of 750 to 900 ms in our case) that allows the processor to identify the provenance of trains of pulses. If a pulse is received by four or more hydrophones positioned in different horizontal planes, the tracking system can reconstruct the full spatial information of the transmitter. For this study four HTI Model 590 hydrophones were deployed on the riser lines from the anchor blocks as per Figure 2, two of them on diagonally opposite lines at about 1 m below the surface, the other two at 8 to 10 m depth depending on the local bathymetry (the lake floor sloped upward gradually approaching the shore, and the hydrophones were kept at least 1 m above the anchor blocks). The distance of the hydrophones relative to each other is a crucial parameter in the tag position calculations, but it did not have to be measured precisely when the system was deployed since a dimensional self-calibration of the array was carried out prior to the tracking runs. This was done by means of a "pinger ring" procedure in which an ultrasonic transmitter embedded in each of the hydrophone assemblies is activated in turn and measured by the other three receivers, allowing the relative distances to be determined from acoustic time of flight calculations. As in the case of the acoustic monitoring hydrophones, shielded coaxial cables laid out on the lake bottom carried the signals to the processing system on shore. Figure 6 shows the various components of equipment in the instrumentation tent for both fish tracking and sound level monitoring.

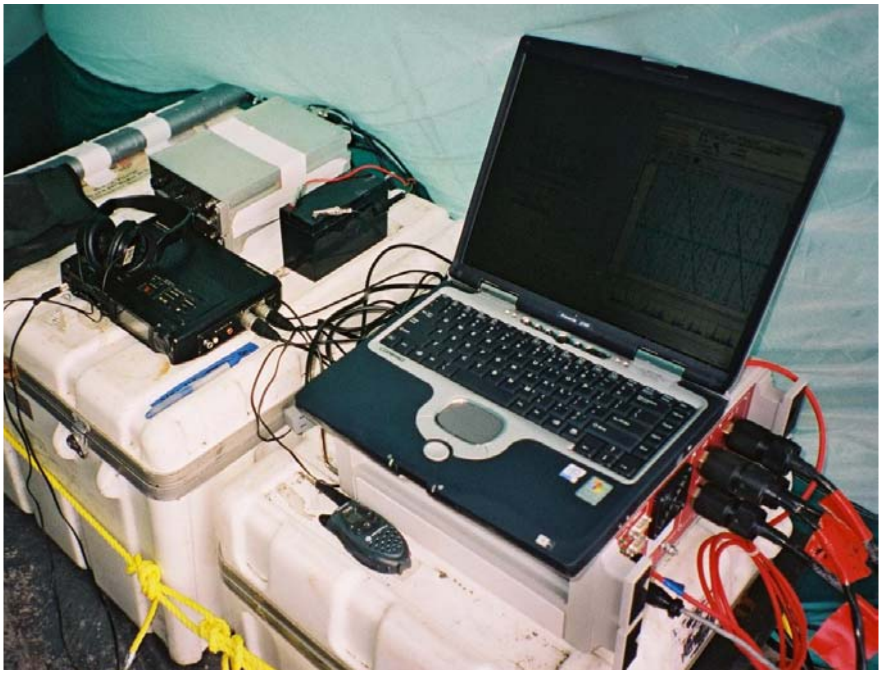

Figure 6: Shore based instrumentation. In the foreground is the HTI Model 291 fish tracking processor, linked via network cable to a notebook PC running the control software; in the background are the amplifiers, batteries and digital recorder for sound level monitoring.

Deterrent devices

For this project we selected two evaluation deterrent devices representing each of the major fish deterrent classes, namely underwater strobe light systems and a multi-frequency acoustic projectors. Strobe lights have been reported to perform well as fish deterrents when operating at rates of 200 to 500 flashes per minute (Maiolie *et al.* 1999, Turnpenny *et al.* 1998), especially with freshwater species, while for acoustic sources there is reported evidence of good performance with various fish species for sound projectors operating at swept frequencies between a few tens and a few thousands of hertz (Turnpenny *et al.* 1998). It should be noted that ultrasonic projectors operating around 125 kHz have been shown to be effective on clupeid fish such as herrings and shads but not on other species (Turnpenny *et al.* 1998), and would therefore be inappropriate for the subjects of relevance to this study.

We used as the visual deterrent test device a compact commercial xenon strobe light with a brightness of about 20 lumens, installed in a custom underwater enclosure (Figure 7, left panel). It was powered externally through a cable, and the flash rate was adjustable via a controller at the surface end. We estimated that this light source would allow evaluation of deterrent performance at distances of at least 10 m in water of sufficient clarity, particularly in low daylight and at night. Because of the directional nature of the output, accurate aiming at depth toward the centre of the net pen had to be ensured; for this purpose we had equipped the strobe unit with an externally mounted UWINSTRU underwater attitude measurement instrument (JASCO Research Ltd) that transmitted the pitch, roll and heading of the assembly via serial cable to a portable computer on the deployment boat. In actual practice, due to the difficulty of monitoring the instrument readouts and adaptively adjusting the aim from the unstable platform of a small boat, we found it more feasible to set the correct heading by visual observation of the light beam briefly tilted upward and then bring the unit to level attitude, relying on the suspension ropes at the front and back to maintain the orientation. Two light deterrent tests were performed on each of the groups of fish subjected to trials, at strobe rates of 4 and 8 pulses per second (240 and 480 pulses per minute) respectively.

Figure 7: (Left) Underwater xenon strobe light with orientation monitoring unit mounted on top; (Right) Underwater acoustic source consisting of low-frequency piezoelectric transducer (on boat seat), power amplifier unit, and digital recorder for playback of pre-programmed waveforms.

For the acoustic deterrent test source we selected a Broadband Acoustic Transmission System (BATS) from Sensor Technology Ltd, consisting of a power audio amplifier matched to a piezoelectric underwater transducer. We requested from the manufacturer a custom transducer capable of more efficient output at frequencies down to 50 Hz, thus permitting the investigation of low-band frequency sweeps. A variety of test signals consisting of swept-frequency waveforms were created ahead of time at JASCO Research using a PC-based programmable signal generator and pre-recorded on Microdrive digital media. These stored waveforms could be played back into the BATS in any order using a Marantz PMD690 digital audio recorder identical to the one used on shore for acoustic level monitoring. The complete system installed on the inflatable boat is shown in Figure 7 (right panel). The transducer was lowered in the water from the boat once the latter was tied up at a deployment station. Despite the asymmetric design of the transducer its output at the frequencies used is essentially omni-directional, thus requiring no aiming. A consistent source depth of 5 m (approximately mid-depth in the water column, and level with the monitoring hydrophones) was used for all the acoustic deterrent trials.

Testing procedures

Fish response monitoring

Once the HTI acoustic tracking equipment had been set up and the hydrophone positional data (from the "pinger ring" measurements and calculations) had been entered in the software configuration along with various other parameters, the system operated essentially as a turn-key application. The tracking software, running on a notebook PC connected to the processing unit, recorded to disk files the raw signal strength, pulse profile and arrival time information at the various hydrophones for every ping received from all the tags in the pen. These data could be later analyzed to yield individual swimming trajectories. According to system specifications, real-time tracking of fish motion and its immediate display should have been possible; this capability, however, was never realized because of a problem with the software that could not be resolved in the field even with the telephone support of HTI personnel. The monitoring of fish response was therefore performed "blind" until post-processing was carried out.

Fish tracking runs generally spanned a half hour interval, with the exception of some of the strobe light trials—to be described later—for which the tracking system was left running over a longer period that encompassed two deterrent test cycles. In the standard runs the tracking software was started about ten minutes ahead of the activation of the deterrent stimulus, thus providing baseline monitoring of the swimming behaviour of the subjects in the pen. Tracking continued through the stimulus period (one minute) and for twenty minutes post-stimulus to document the return to baseline behaviour of the fish after a possible reaction to the deterrent. No less than half an hour separated consecutive exposures of the fish to deterrent stimuli, even for back-to-back trials. The HTI software inserts in the header of its output files the start time of the tracking based on the PC clock, and precisely times each data point relative to that reference; the stimulus period was also timed by the operator based on the PC clock or a chronograph synchronized with it, thus allowing correlation of the tracking data with the stimulus to within one second.

Sound level monitoring

During all the acoustic deterrent trials the underwater sound signal at two hydrophone locations was monitored and recorded. With the exception of the case where the source was deployed at station ST0, the direct sound propagation ranges to the two hydrophones bracketed those to any location within the experimental pen. To a first approximation, neglecting multi-path effects from surface and bottom reflections and assuming a simple spherical spreading loss, the sound levels within the pen can thus be expected to lie between those measured at the hydrophones. Under this simplifying assumption it is possible to estimate the sound level throughout the pen for each acoustic deterrent trial from the measurements at the hydrophones (in fact a single hydrophone would suffice, but having two allows some cross-validation and averaging).

In the course of a trial the acoustic monitoring instrumentation on shore was readied for a recording shortly before the activation of the sound source. Aside from shutting down the generator to reduce electrical interference as previously noted, the only preparation required was to set the gains on the two Ithaco amplifiers to previously determined levels, ranging from +20 dB to +40 dB depending on the distance of the source, that would provide adequate signal amplitude to the digital recorder. Some twenty seconds prior to stimulus onset the Marantz digital recorder was started in acquisition mode and left running until about twenty seconds after stimulus end. While the sound source was operating the amplified signals from the hydrophones would be aurally monitored for strength and distortions through stereo headphones.

Deterrent deployment and operation practices

The methodology for positioning, deploying and operating the deterrent test sources was designed to minimize the potential for affecting fish behaviour with spurious stimuli such as boat engine noise and other sounds at close range. This was particularly important for the strobe source tests, which took place directly adjacent to a side of the net pen, and the acoustic source tests conducted at stations ST0 and ST1.

For the strobe light deterrent tests the procedure followed on the first day of trials (14 October) differed from subsequent days in several respects. To begin with, the strobe trials on that date were conducted in daytime on a heavily overcast late morning and early afternoon, which did not provide an optimal contrast for the strobe flashes despite the low ambient light level. Secondly, the two tests at four and eight pulses per second (pps) were conducted in separate tracking runs with the boat leaving the deployment location during the interval between them. Lastly, the source deployment depths for the two tests were different from each other and from subsequent days' trials. In the 4 pps test the strobe light assembly was lowered to a depth of 10 m and pointed about 30 degrees upward, using the UWINSTRU readouts to maintain its aim. As this proved very difficult to perform even with two operators on board, in the subsequent 8 pps test the system was aimed visually as described in an earlier section; to do this the depth of deployment had to be reduced to about 3 m to be able to see the strobe beam at a slant over the ambient light level (the assembly itself could not be seen at all at that depth). For later strobe deterrent trials the procedure was revised to address the issues that we had identified. The trials took place in darkness (in the early morning and late evening of the 16th of October); the tests at 4 and 8 pps were conducted over a single, extended tracking run to minimize boat movement near the pen as we shall describe, and the source was deployed at a depth of 6 m—which in preliminary night-time tests was found to permit visual adjustment of the beam aim as previously mentioned. At the beginning of the tracking run the boat was brought into position near the side of the pen under minimum engine power or paddle and tied up to the net. The strobe source, preset at one of the two test flash rates, was lowered into the water some ten minutes ahead of the first stimulus period and approximately oriented using its suspension ropes. At a precise time—based on a chronograph synchronized with the tracking PC on shore—the strobe was activated and its aim rapidly adjusted; one minute later it was switched off. The boat remained in place, with the source in the water and minimum movement on board, for about 30 minutes; during this time the other test flash rate was set. The strobe was then activated again at a precise time for one minute. After being switched off the source was raised into the boat, which was then brought some distance away from the net under paddle and on to shore under low engine power. Tracking was allowed to continue for about 20 minutes after the second stimulus period.

The procedure for the acoustic deterrent tests, despite the greater complexity of the apparatus, was significantly less involved than for the strobe light because the transducer did not require aiming. A single operator on the boat, in contact with the shore via FRS radio, handled the positioning and tie-up at station, the deployment of the transducer and the control of the sound generator. A second operator on shore controlled the fish tracking system and the acoustic recording equipment and directed over the radio the activation of the deterrent signal. The sequence of operational steps in a trial differed slightly depending on whether the source was deployed at close range from the net pen (stations ST0 and ST1) or at greater distance (ST2 and ST3). In the first case special measures were taken to minimize disturbance to the fish from spurious noise during the experimental period: the boat was brought to the deployment station under minimum engine power or paddle, the engine cut and the transducer lowered in the water before the ten minute interval of baseline tracking was initiated. In the second case, given the significant separation from the pen, the boat proceeded to the deployment station under low power while the baseline tracking was already underway. The stimulus delivery procedure was the same in all cases: on a first cue from the shore, several seconds before the planned deterrent activation time, the operator on the boat started playback of a specified audio track on the digital recorder with the BATS amplifier volume set to zero; on a second cue precisely based on the PC clock the volume was sharply raised to maximum, thus beginning the stimulus period; on a third cue one minute later the volume was cut again. Shortly after delivering the stimulus the operator raised the transducer into the boat and proceeded to shore, under paddle alone if in close proximity of the net pen. Over the course of all the acoustic deterrent trials a total of six different tonal patterns were tested, though the last four in the set were only added for the final group of fish in the study in an effort to identify a more effective deterrent at a single close-range deployment distance. The tonal patterns were as follows:

A. 1 kHz to 3 kHz ramp, four cycles per second
B. 50 Hz to 500 Hz ramp, four cycles per second
C. 50 Hz to 1 kHz ramp, four cycles per second
D. 50 Hz to 100 Hz ramp, four cycles per second
E. 1 kHz to 3 kHz sweep, two cycles per second
F. 50 Hz to 1 kHz sweep, two cycles per second.

In the above list, the term "ramp" denotes a tonal pattern rising linearly from the lower to the upper frequency limit and dropping suddenly back, while "sweep" denotes a pattern rising and falling linearly between the frequency limits. We gave greater representation to ramps over sweeps in our choice of patterns on the premise that a tonal scan interspersed with discontinuities should have more of a combined startling effect on the fish; indeed Turnpenny *et al.* (1998) relate that effective acoustic deterrent signals are characterized by rapid changes in frequency and provide an example of a ramp-type tonal pattern.

Analysis procedures

Sound level analysis

We processed the acoustic monitoring information using a powerful scientific data analysis and presentation tool, IDL (Interactive Data Language) from Research Systems Inc. From the recordings of the measured sound pressure waveforms we computed an average sound pressure level (SPL) for each acoustic deterrent test at both hydrophone locations as follows. The digitally recorded waveform was high-pass filtered to eliminate noise below 20 Hz and divided into contiguous one-second intervals. The raw SPL for each interval was computed as 10 log(msv) where msv is the mean square value of the signed digital data for that interval; this was converted to a calibrated SPL in dB re µPa by applying a gain correction that accounted for hydrophone sensitivity, amplifier gain setting and recorder calibration. The average of these one-second samples over the duration of the stimulus period gave the mean SPL for that particular test at the hydrophone location.

Assuming a pure spherical spreading loss as a simplifying approximation, from the mean SPL value at a hydrophone and the range from the acoustic transducer we estimated the source level (SL) based on the measurements at that hydrophone as SL = SPL + 20 log(r). The agreement between the SL values based on the two hydrophones was generally quite good over the various trials, with an average discrepancy of about 3 dB, supporting the validity of the spreading loss approximation. We then used the average of the two SL estimates to compute, for each acoustic deterrent test, the SPL at the proximal and distal walls of the experimental pen in direct alignment with the source (that is, along the centreline of the pen). This provides an indication of the acoustic levels to which the fish were subjected for a particular deterrent test and the gradient across the experimental pen.

Fish motion analysis

The purpose of using an advanced ultrasonic fish tracking system in these trials, with all the procedural complexity that such an approach entailed, was to obtain a very precise record of the motion of each subject so that every nuance of their response to a deterrent stimulus could be analyzed on an individual or statistical basis. In order for this goal to be achieved the accuracy of the tracking system had to be exploited to its full potential. Although the HTI Model 291 system is in itself capable of sub-metre resolution in its processing of tag pings arrivals and in principle can provide time histories as detailed as the pinging frequency of a given tag (in the order of one point per second), we found that—at least for the experimental configuration that we used—it was not possible to even approach these performance levels relying solely on the automatic processing capabilities of the software. Aside from the impasse with real-time tracking that was mentioned earlier, if the HTI AcousticTag software was used to post-process the stored pings arrival data without any manual classification of the latter the resulting three-dimensional paths were extremely sparse, yielding at best a few tens of points per tag for an entire half-hour tracking of eight or so tags. This appeared to be due to the fact that the software would use none but the most unequivocal of the ping arrivals in data. The involvement of a human operator was therefore essential in the process of identifying the times of first arrival of individual tag pings at each of the four hydrophones, discarding spurious arrivals due to multi-path propagation. This is done using the HTI ping selection software MarkTags, which presents the user with a scattergram of ping arrival times at a selected hydrophone, modulo a particular tag's repetition period, versus tracking time (the individual points can also be encoded in size and/or colour to convey additional information such as ping strength). Consecutive ping arrivals from the tag whose period is selected will line up in the scattergram if the tag is stationary (as each ping arrives at the hydrophone at a constant interval equal to the modulo) forming either a horizontal line if the match is exact or a gently sloping diagonal if the tag's repetition rate is slightly off its nominal value. Changes in the distance between the tag and a hydrophone due to motion of the subject cause modulations in the time of arrival from its linear baseline, still generally preserving a discernible continuity over time that enables the visual identification of the correct pings. The analyst using MarkTags has available a set of tools allowing the selection of individual pings or, more commonly, groups of pings within an outline drawn on the plot; the software takes care of accepting only the first arrival within the selection outline at each time step. This apparently straightforward if laborious process is complicated by several factors. The first is the presence in the scattergram of hundreds of points denoting ping arrivals from all the other tags, which having a mismatching period either line up along steep diagonals or appear in an essentially random pattern; these can significantly hamper the identification and selection of the aligned pings. The second is the presence of multipath arrivals (tag pings echoed by reflectors such as the water surface or bottom) which if originating from the selected tag appear as stratified lines parallel to the primary arrival at longer propagation times. These in themselves would not be arduous to reject were it not for the last complicating factor, namely the occasional and sometimes significant dropout of ping arrivals from the scattergram that may be due to an obstacle blocking the sound path or the system rejecting a ping in marginal signal to noise conditions. In such cases it may be difficult to identify in the broken sequence of points whether an aligned cluster is a direct arrival or not, and the software itself may pick multipath echoes within a slackly drawn selection outline wherever direct arrival points failed to register. Skipping from direct to multipath arrivals in the ping analysis is the primary cause of jitter in the reconstructed tag tracks. This complexity of identification may explain why the system fares poorly in the unassisted processing of the original acquired data. As it were we spent considerable effort in the careful manual selection of arrivals for each individual tag, hydrophone and tracking run in the study, thus providing an excellent input to the trajectory reconstruction algorithm in the HTI software. The result are highly accurate records of fish motion that fully meet the objectives of the ultrasonic tracking approach.

From the spatial tracking data for each fish in an experimental group we generated a variety of analytical plots designed to provide insight on specific aspects of the subjects' behaviour before, during and after exposure to the stimuli. For this processing we also used IDL as the analysis and presentation tool. The types of plots created, with the motivation for their use, are listed below.

a. To provide an overview of the swimming activity and extent of use of space for each fish in an experimental group over the course of a trial we generated planar (x-y) plots of the complete trajectories with encoding of the depth (z) as colour.

b. To allow the identification of changes in the planar motion of each fish that may be linked to the deterrent we generated x-y plots of the swim paths for five minutes of tracking centred at the one-minute stimulus period, drawing the path segment for each minute in a different colour to show the temporal correlation with stimulus onset and termination.

c. To provide a time correlated analysis of the vertical motion of each fish relative to deterrent activation we generated t-z plots for the complete tracking runs, with the stimulus interval bracketed by vertical bars. In creating these plots we had to smooth to some extent the tracked z position, which is noisier than the other two dimensions due to the shorter vertical baseline of the hydrophone array; we found that a 30-point sliding average filter, with an equivalent time window of 22-25 seconds depending on a tag's ping rate, provided a satisfactory balance between effective noise reduction and damping of temporal response in the graph.

d. To reveal, on a statistical basis, responses to deterrent stimuli that might not necessarily have resulted in a significant alteration of position or path we graphed the change in the mean spatial swim speed (computed by backward differences) between contiguous one-minute intervals aligned with the stimulus period, averaged for all members of a species in an experimental group. Prior to computing the instantaneous velocity vector components to obtain swim speed we smoothed the z position as described above.

Results and discussion

Experimental records

Over three sets of trials on the 14th, 15th and 16th of October 2003, a total of twenty fish were successfully studied out of twenty-three captured and tagged. A significant number of subjects of various species including inconnu, lake trout and northern pike that were being kept in the holding pens prior to being tagged were lost to a poaching incident on the night of 10 October, a serious setback given the progressive worsening of fishing conditions as temperatures dropped (a guard was subsequently posted at the experiment site to stave off the risk of further thefts). Table 1 summarizes the species and sizes of the fish that made up the three experimental groups. The tagged subjects that failed to contribute data to the study are identified in the table by a grey background; as the table comments indicate, causes of failure included the accidental early escape of a lake whitefish after tagging and two episodes of tag regurgitation on the last day of trials, one by a lake trout as it was being transferred from the boat into the main pen (the fact went unnoticed until after the animal was in the pen) and one by an inconnu after it had been for two hours in the pen but before any tests had taken place. In the latter two cases there was no further stock of the same species available to supplant the subjects, and the option of retrieving the animals from the main pen for re-tagging was ruled out because of the stress that such an operation (which would have required raising the floor of the net pen) would have caused to all the fish in the group. Given the closing in of the ice on the lake, a postponement of the last set of trials to perform the retrieval and give time to the fish to acclimatize once more would have been an unacceptable risk. A final observation regarding the composition of the three experimental groups is the fact that one subject in each of the first and second groups, identified in the table by a yellow background, was missed in the retrieval (and presumed escaped over the edges of the raised net pen) but was then discovered among the tracked fish in the next group's trials. In these cases the rogue subject of a different species was simply treated separately in the analysis.

Table 1: Fish tagging and testing summary.

Date Tagged	Date Tested	Species	Tag period (ms)	Fork length (cm)	Comments
12 Oct	14 Oct	Lake Whitefish	750	42.0	
12 Oct	14 Oct	Lake Whitefish	760	41.0	
12 Oct	14 Oct	Lake Whitefish	770	42.0	Tagged and accidentally released into open lake
12 Oct	14 Oct	Lake Whitefish	780	43.0	
12 Oct	14 Oct	Lake Whitefish	790	41.0	
12 Oct	14 Oct	Lake Whitefish	810	45.0	
12 Oct	14 Oct	Lake Whitefish	820	41.5	
12 Oct	14 Oct	Lake Whitefish	830	44.5	
12 Oct	14 Oct	Lake Whitefish	840	40.5	Remained in pen through next group's trials (15 Oct)
15 Oct	15 Oct	Northern Pike	750	53.0	
15 Oct	15 Oct	Northern Pike	760	54.0	
15 Oct	15 Oct	Northern Pike	780	53.5	
15 Oct	15 Oct	Northern Pike	810	51.0	
15 Oct	15 Oct	Northern Pike	820	55.0	
15 Oct	15 Oct	Northern Pike	830	54.0	
15 Oct	15 Oct	Northern Pike	790	54.0	Remained in pen through next group's trials (16 Oct)
16 Oct	16 Oct	Broad Whitefish	810	49.0	
16 Oct	16 Oct	Broad Whitefish	860	43.0	
16 Oct	16 Oct	Broad Whitefish	900	44.0	
16 Oct	16 Oct	Inconnu	850	74.0	
16 Oct	16 Oct	Inconnu	760	57.0	Regurgitated tag in main pen at beginning of trials
16 Oct	16 Oct	Lake Trout	880	64.0	
16 Oct	16 Oct	Lake Trout	750	63.0	Regurgitated tag just prior to transfer into main pen

The details of the deterrent trials carried out on each experimental group are summarized in Table 2. Each experimental group of fish corresponds to one date of the trials with the exception of the second group that was mostly tested on the 15th of October but was put through the visual deterrent trials on the morning of the 16th. The tracking ID (based on the starting day, hour and minute of a run) was automatically generated by the HTI software to identify all data files related to that run; it is used here as the primary cross-reference to the various graphs and other results presented in this section and in the Appendix. The start times for the tracking and the stimulus in a trial were logged to within one second accuracy as they are crucial for correlating the activity of each fish with the deterrent signal. The duration of the stimulus, as mentioned before, was exactly one minute. Most of the tracking runs cover a period of about half an hour, with the previously noted exception of the visual deterrent trials on 16 October in which each tracking record (2890801 and 2892015) encompassed two consecutive tests. Records 2871116 and 2891408 contain, respectively, a longer than usual pre-stimulus and post-stimulus tracking interval and thus run for about 40 minutes, while record 2871700 was cut short by a network cable disconnection a few seconds after the end of the stimulus and thus contains no post-deterrent recovery tracking.

Table 2: Details of the deterrent trials.

Date	Tracking ID	Tracking Start Time	Stimulus Start Time	Tracking End Time	Deterrent type	Deterrent location
14 Oct	2871116	11:16:21	11:35:00	11:57:06	4 pps strobe light	At pen side; 10 m depth
	2871240	12:40:34	12:50:00	13:11:16	8 pps strobe light	At pen side; 3 m depth
	2871338	13:38:50	13:49:00	14:09:27	1 kHz – 3 kHz ramp	ST1 (15 m); 5 m depth
	2871415	14:15:24	14:26:00	14:47:16	50 Hz – 500 Hz ramp	ST1 (15 m); 5 m depth
	2871536	15:36:06	15:45:00	16:05:07	1 kHz – 3 kHz ramp	ST2 (30 m); 5 m depth
	2871625	16:25:20	16:35:00	16:55:08	50 Hz – 500 Hz ramp	ST2 (30 m); 5 m depth
	2871700	17:00:40	17:10:00	17:11:34	1 kHz – 3 kHz ramp	ST3 (45 m); 5 m depth
	2871740	17:40:19	17:50:00	18:10:16	50 Hz – 500 Hz ramp	ST3 (45 m); 5 m depth
15 Oct	2881408	14:08:48	14:18:00	14:38:14	1 kHz – 3 kHz ramp	ST1 (15 m); 5 m depth
	2881441	14:41:11	14:51:00	15:11:17	50 Hz – 500 Hz ramp	ST1 (15 m); 5 m depth
	2881516	15:16:04	15:26:00	15:46:39	1 kHz – 3 kHz ramp	ST2 (30 m); 5 m depth
	2881547	15:47:22	15:57:00	16:17:31	50 Hz – 500 Hz ramp	ST2 (30 m); 5 m depth
	2881618	16:18:21	16:28:00	16:48:09	1 kHz – 3 kHz ramp	ST3 (45 m); 5 m depth
	2881649	16:49:27	17:02:00	17:23:35	50 Hz – 500 Hz ramp	ST3 (45 m); 5 m depth
	2881802	18:02:57	18:12:00	18:32:20	1 kHz – 3 kHz ramp	ST0 (5 m); 5 m depth
	2881834	18:34:44	18:44:00	19:05:13	50 Hz – 500 Hz ramp	ST0 (5 m); 5 m depth
16 Oct	2890801	08:01:08	08:30:00	09:30:07	8 pps strobe light	At pen side; 6 m depth
			09:00:00		4 pps strobe light	At pen side; 6 m depth
16 Oct	2891408	14:08:41	14:20:00	14:48:12	1 kHz – 3 kHz ramp	ST0 (5 m); 5 m depth
	2891500	15:00:16	15:10:00	15:30:13	50 Hz – 500 Hz ramp	ST0 (5 m); 5 m depth
	2891537	15:37:04	15:47:00	16:07:21	50 Hz – 1 kHz ramp	ST0 (5 m); 5 m depth
	2891628	16:28:43	16:39:00	17:00:04	50 Hz – 100 Hz ramp	ST0 (5 m); 5 m depth
	2891716	17:16:21	17:26:00	17:46:12	1 kHz – 3 kHz sweep	ST0 (5 m); 5 m depth
	2891749	17:49:37	17:59:00	18:20:01	50 Hz – 1 kHz sweep	ST0 (5 m); 5 m depth
	2892015	20:15:43	20:45:00	21:30:08	4 pps strobe light	At pen side; 6 m depth
			21:15:00		8 pps strobe light	At pen side; 6 m depth

Acoustic deterrent sound levels

The estimated sound pressure levels (SPL) at the BATS acoustic source and at the walls of the experimental pen proximal and distal to it are reported in Table 3 for each of the deployments of the acoustic deterrent. The tracking ID corresponding to each deployment is included for ease of correlation with other results. If the BATS amplifier and acoustic transducer were operating at exactly the same power output and efficiency from one deployment to the next, the estimated source levels—at least for a particular acoustic waveform—should be essentially constant regardless of the station at which the source was deployed. In fact this may not be quite the case as the source level is estimated from the measurements at two fixed hydrophone locations (thus at different ranges depending on the deployment station) using some basic simplifying assumptions for the propagation loss as described in the data analysis section.

Table 3: Estimated sound levels at the BATS source and at the pen walls

Date	Tracking ID	Station	Acoustic waveform	Source Level (dB re µPa)	SPL at Prox. Wall (dB re µPa)	SPL at Distal Wall (dB re µPa)
14 Oct	2871338	ST1	1 kHz – 3 kHz ramp	153.30	129.78	125.35
14 Oct	2871415	ST1	50 Hz – 500 Hz ramp	146.30	122.77	118.34
14 Oct	2871536	ST2	1 kHz – 3 kHz ramp	154.84	125.29	122.80
14 Oct	2871625	ST2	50 Hz – 500 Hz ramp	144.33	114.79	112.29
14 Oct	2871700	ST3	1 kHz – 3 kHz ramp	151.25	118.19	116.45
14 Oct	2871740	ST3	50 Hz – 500 Hz ramp	148.48	115.42	113.68
15 Oct	2881408	ST1	1 kHz – 3 kHz ramp	158.27	134.74	130.31
15 Oct	2881441	ST1	50 Hz – 500 Hz ramp	148.26	124.74	120.30
15 Oct	2881516	ST2	1 kHz – 3 kHz ramp	144.48	114.94	112.44
15 Oct	2881547	ST2	50 Hz – 500 Hz ramp	135.17	105.63	103.13
15 Oct	2881618	ST3	1 kHz – 3 kHz ramp	156.14	123.08	121.34
15 Oct	2881649	ST3	50 Hz – 500 Hz ramp	147.47	114.41	112.67
15 Oct	2881802	ST0	1 kHz – 3 kHz ramp	154.87	140.89	131.35
15 Oct	2881834	ST0	50 Hz – 500 Hz ramp	146.50	132.52	122.98
16 Oct	2891408	ST0	1 kHz – 3 kHz ramp	157.51	143.53	133.99
16 Oct	2891500	ST0	50 Hz – 500 Hz ramp	147.49	133.51	123.97
16 Oct	2891537	ST0	50 Hz – 1 kHz ramp	153.39	139.41	129.86
16 Oct	2891628	ST0	50 Hz – 100 Hz ramp	140.90	126.93	117.38
16 Oct	2891716	ST0	1 kHz – 3 kHz sweep	159.45	145.47	135.92
16 Oct	2891749	ST0	50 Hz – 1 kHz sweep	155.16	141.19	131.64

For each of the acoustic waveforms that were used repeatedly in the study, namely the 1 kHz – 3 kHz ramp and the 50 Hz – 500 Hz ramp, we observe from the table that the estimated source levels are mostly quite consistent—with one notable exception in both cases for the deployments at ST2 on 15 October. If we exclude those deployments, the average source levels (mean ± s.d.) are 155 ± 2 dB re µPa for the 1 kHz – 3 kHz ramp and 147 ± 1 dB re µPa for the 50 Hz – 500 Hz ramp. The levels for the outlier points are about 10 dB lower than the mean for each of the waveforms, a discrepancy that is difficult to explain except possibly in terms of a temporary sagging in the output of the battery powering the BATS. The source levels for the additional deterrent waveforms used on the last day cannot be similarly corroborated as only single instances were recorded, but they appear reasonable and indeed point to the fact that the BATS, even with the custom low-frequency transducer, dropped significantly in transmitted acoustic level at frequencies below 100 Hz.

The estimated sound pressure levels at the proximal and distal walls, which can be assumed to encompass the range of sound intensity that fish in the pen might experience from the deterrent, are certainly above ambient background but not extremely strong even with the source at the closest station. It is very unlikely that any species would find such noise levels uncomfortable or noxious from a physiological standpoint as they are at least 25 dB lower than the 180 dB re µPa minimum hearing injury level referenced earlier.

Any deterrent outcome, therefore, would be expected to arise from the startling or frightening effect of a sudden and unusual sound of the appropriate tonal pattern; if such a reaction could be observed for at least one of the test waveforms, then presumably a more powerful sound projector could extend its effectiveness and range.

Swimming behaviour

The motion tracking of the several subjects in each group through the various deterrent tests performed over the three days of trials generated a large amount of very detailed swimming behaviour information. The graphical records from the processing of single-subject tracking data, as per methods a. through c. in the "Fish motion analysis" section, are included in their entirety in the Appendix. For most of the trials the analytical documentation consists of three charts or collections of plots (one plot per individual):

- full path x-y tracks showing the overall motion over the duration of the trial, with depth encoded as colour from green (surface) to blue (~12 m);
- peristimulus x-y tracks representing five minutes of motion centred at the stimulus period, with one-minute time intervals encoded as colour: black (stimulus-2 min), blue (stimulus-1 min), red (stimulus), yellow (stimulus+1 min) and green (stimulus+2 min);
- depth versus time plots, with the start and end points of the stimulus interval overlaid as vertical bars on the graph.

Instances of the above are Charts 1–3 to 46–48 and 53–56 to 68–70 in the Appendix. In the case of trials in which two deterrents (different strobe light pulse rates) were tested over a single tracking, four collections of plots are presented: full path plots for the entire trial duration, two distinct sets of peristimulus x-y tracks—one for each test, and depth versus time plots for the whole trial duration with both stimulus intervals identified by vertical bars. The only two such instances are Charts 49–52 and 71–74.

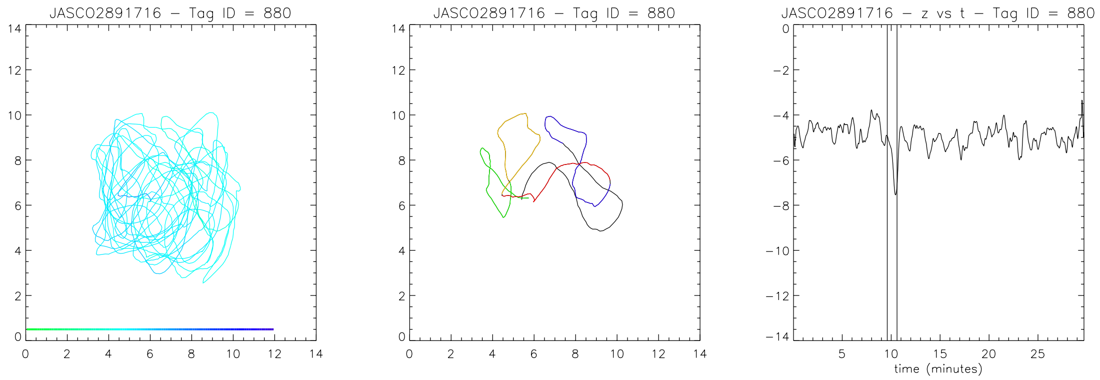

Figure 8: Sample analytical plots from the tracking data for a lake trout subjected to a 1 kHz – 3 kHz sweep pattern acoustic deterrent at station ST0 (record 2891716, Tag ID 880). From left to right: full path x-y tracks with depth encoded as colour; peristimulus x-y tracks with 1-min time reference encoded as colour (black-blue-red-yellow-green); depth vs time graph with stimulus interval shown.

Figure 8, which groups together plots also found in Charts 65–67 in the Appendix, gives an example of the detail in which a subject's activity is tracked over the course of a deterrent trial. It also presents one of the most evident episodes of reaction to a deterrent stimulus that were encountered in this study. The track plot in the left pane provides a complete view of the motion pattern of the subject, a lake trout, over the half-hour trial period (in these plots the net pen nominally extends between the 2 m and 12 m marks along each axis, but its sides were distorted to some extent due to water flow). This overall record of activity is of significant value in assessing the motility of a subject and any dwelling preferences within the volume of the pen that could have affected a behavioural response. We found a remarkable dependence of the swimming pattern on species (see Figure 9). Northern pike, for example, exhibited a tendency to "hug" very closely a side of the net pen and swim alongside it in a continuous back and forth pattern; broad whitefish and the single tagged lake trout generally moved in convoluted planar patterns exploring indifferently all regions of the pen, while the inconnu mostly swam in regular concentric loops well clear of the sides of the net. We also observed behavioural differences—to the limited extent that we could document them given the scheduling of the trials—between daylight and night hours. In near darkness, northern pike tended to remain still for long periods of time at various depths, occasionally moving to a different location by following the contour of the pen (see Chart 49 in the Appendix) whereas broad whitefish, inconnu and lake trout altered their swimming patterns to a more erratic motion that would take them much closer to the sides of the pen than in daylight (see Chart 71 in the Appendix).

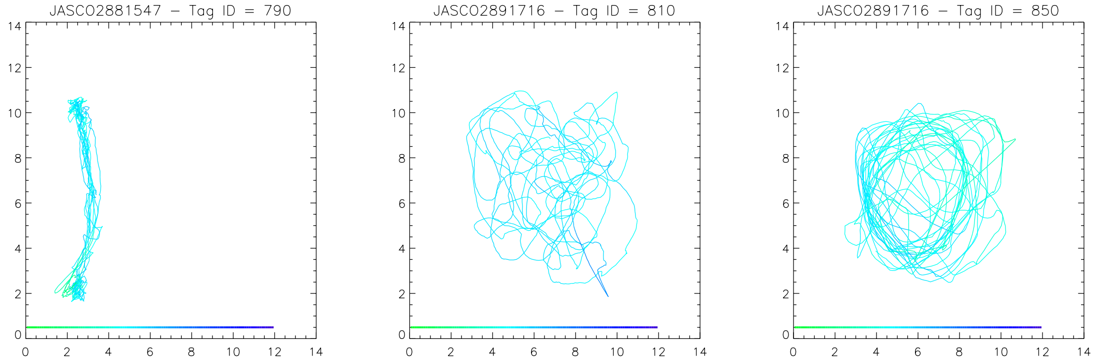

Figure 9: Full path x-y tracks, with depth encoded as colour, for a northern pike (left), a broad whitefish (centre) and an inconnu (right) over 30-minute periods. These are typical of the majority of daytime trials involving one or more individuals of these species. See also Figure 8, left pane, for an example of a lake trout track.

Returning now to Figure 8, the plot in the central pane provides a time-referenced record of the trout's planar (x-y) motion immediately prior, during and following the stimulus interval. In these plots the deterrent source is always located to the right; in the current example it is at ST0, three scale metres beyond the right axis of the graph. At the onset of the 1 kHz – 3 kHz sweep acoustic stimulus (marked by a transition from the blue to the red segment of the track) the subject was swimming within 1 m of the pen wall proximal to the source and near its centreline, having just turned to a direction parallel to the wall. After the start of the stimulus the fish turned inward from the wall, though not abruptly, and swam away from the source toward the middle of the pen. The end of the one-minute stimulus interval (marked by a transition from the red to the yellow segment) coincided with an abrupt change in the direction of swimming. The depth versus time plot in the right pane of the figure reveals that a response also took place in the vertical motion of the fish, which dove from 5 m to 7.5 m during the stimulus period and rapidly returned to its original depth after the sound subsided.

Similar instances of swimming behaviour indicative of some avoidance response in individual subjects were found, by visual inspection, in a few of the analyzed tracking records in the Appendix. They are summarized in Table 4, which documents the type and location of the deterrent and the species and tag IDs of the subject(s) that appeared to react. In selecting these events we took care to disregard cases where a change in motion pattern seemingly correlated with the stimulus might have been coincidentally caused by the fish encountering a wall of the net pen, which can also induce a diving or rising response. This applied particularly to the trials involving northern pike because of these subjects' tendency to shuttle between two contiguous corners of the pen.

Table 4: Summary of trials in which one or more subjects appeared to exhibit some degree of avoidance response to the deterrent stimulus, based on visual inspection of the motion records.

Tracking ID	Deterrent type	Deterrent location	Species and IDs of fish indicating reaction	Relevant charts in Appendix
2871536	1 kHz – 3 kHz ramp	ST2 (30 m)	Lake Whitefish (810, 820)	13, 14, 15
2881516	1 kHz – 3 kHz ramp	ST2 (30 m)	Northern Pike (750)	31, 32, 33
2881834	50 Hz – 500 Hz ramp	ST0 (5 m)	Northern Pike (830) Lake Whitefish (840)	46, 47, 48
2891500	50 Hz – 500 Hz ramp	ST0 (5 m)	Broad Whitefish (860, 900) Lake Trout (880)	56, 57, 58
2891716	1 kHz – 3 kHz sweep	ST0 (5 m)	Inconnu (850), Lake Trout (880)	65, 66, 67
2892015	4 pps strobe light	At pen side	Broad Whitefish (860), Inconnu (850)	71, 72, 74
	8 pps strobe light	At pen side	Broad Whitefish (860), Lake Trout (880)	71, 73, 74

The identification of responses by visual inspection of the tracking records is limited in its scope in that it cannot reveal behavioural changes that do not result in a path alteration, such as a deterrent-induced change in swim speed in a fish already pointed away from the source or constrained along a path by the walls of the pen; it also provides only an assessment of response for single individuals. To address these issues we performed a further analysis of motion behaviour based on the change in spatial swim speed between contiguous one-minute intervals, averaged for all members of a species in a given test group (described as method d. in the "Fish motion analysis" section). The plots thus obtained for all species in the three experimental groups and all deterrent trials to which they were subjected are included in the Appendix as Charts 75 to 81. From those records we selected cases that exhibited an appreciable change in the one-minute average swim speed Δv_{avg} for the stimulus period and for the minute immediately following. The criterion for selection was that Δv_{avg} for the stimulus period and/or the following minute would exceed in magnitude the Δv_{avg} values for at least two one-minute intervals prior and after. Figure 10 shows the selected plots; its caption identifies the deterrent and subject species involved in each case. We should note that the plot for tracking ID

2891716, Tag ID 880 does not strictly meet the stated criterion but was included in the figure because of its relevance to the example of an identified response discussed earlier in this section; this in fact indicates that the Δv_{avg} metric may fail to identify what appears to be unequivocally a reaction.

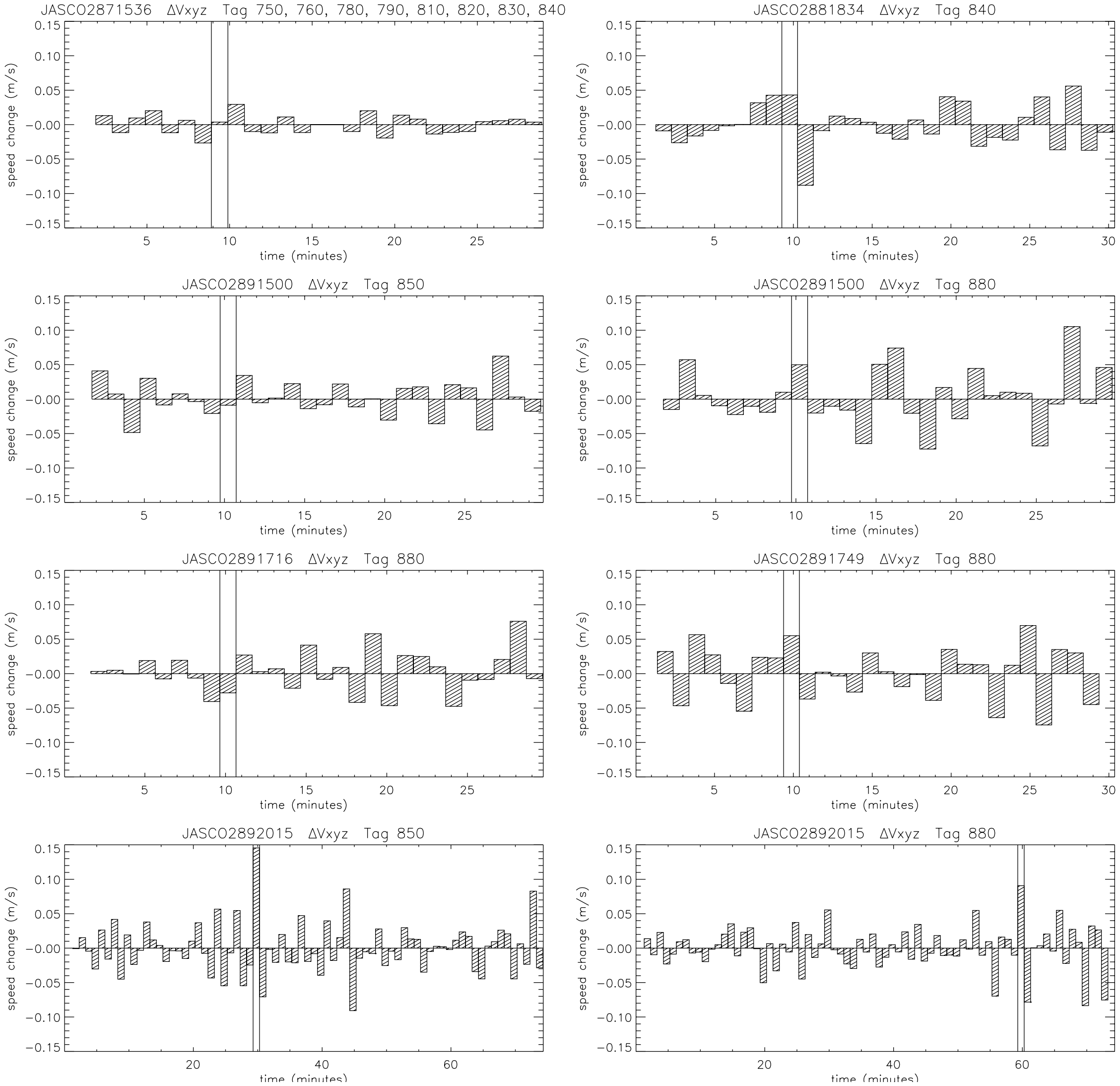

Figure 10: Selected plots of change in mean swim speed between contiguous one-minute intervals aligned with the stimulus period, averaged over all members of a species within an experimental group where applicable. Deterrents and subjects, from top to bottom and left to right, are:

- **2871536: 1 kHz – 3 kHz ramp at ST2, for all seven lake whitefish in the first group;**
- **2881834: 50 Hz – 500 Hz ramp at ST0, for the single lake whitefish in the second group;**
- **2891500: 50 Hz – 500 Hz ramp at ST0, for the single tagged inconnu in the third group;**
- **2891500: 50 Hz – 500 Hz ramp at ST0, for the single tagged lake trout in the third group;**
- **2891716: 1 kHz – 3 kHz sweep at ST0, for the single tagged lake trout in the third group;**
- **2891749: 50 Hz – 1 kHz sweep at ST0, for the single tagged lake trout in the third group;**
- **2892015: 4 pps strobe at pen side, for the single tagged inconnu in the third group;**
- **2892015: 8 pps strobe at pen side, for the single tagged lake trout in the third group.**

The response analysis based on Δv_{avg} corroborates several of the identifications made through visual inspection of the motion records (Table 4) and reveals less obvious reactions, such as the surge in swim speed of the inconnu at the end of the stimulus period for the 50 Hz – 500 Hz ramp signal (record 2891500, Tag ID 850), that may point to some degree of efficacy of that signal on said species. The speed change reaction of the lake trout to the 50 Hz – 1 kHz sweep signal (record 2891749, Tag ID 880) finds no corresponding identification in Table 4 only because the analysis by visual inspection of the tracking records showed the motion during the stimulus period to be toward the source and thus not an avoidance response. The efficacy of the strobe light deterrent in causing a reaction in the inconnu (at 4pps) and the lake trout (at 8pps) is well documented by both the path records analysis and the speed change analysis.

Conclusions

This study, for all its methodological complexity, had the simple aim of identifying a visual or acoustic deterrent signal that would effectively displace a variety of fish species from a volume of water surrounding its source. From that standpoint the project has only succeeded in showing that the candidate deterrents that we evaluated did not meet the requirement. None of the tonal patterns that were tested, nor the strobe light source, had the ability to cause a massive exodus of the test fish from their initial location toward the far recesses of the pen. From the analysis of the sound pressure levels from the BATS acoustic source, which were found to be significantly lower than the manufacturer's nominal specifications would have brought to expect, it can be argued that lack of a sufficient intensity of sound was probably responsible for the failure to elicit such a response. Likewise the light signal from the strobe source was found to carry only for a few metres in the lake water, meaning that its effectiveness as a deterrent would be limited to a very short range.

In the absence of a large-scale reaction, the emphasis of the study then shifted to the detailed analysis of any effect that the deterrents might have induced on the fish, in order to determine whether a particular stimulus was at least noticed by the subjects and, that being the case, whether it elicited any level of evasive response. The motivation of this approach was to identify any would-be deterrent stimuli that merely failed to realize their potential efficacy because of insufficient power level. The methodology and equipment that we had organized for this study had the technical capability of detecting the smallest details in the swimming behaviour of the test subjects. Had there been a major and unequivocal flight reaction to a deterrent this fine tracking capability might have been somewhat superfluous; under the circumstances it proved essential to the study.

From the analysis of the tracking records for three experimental groups of fish containing individuals from five species indigenous to the Mackenzie Delta lakes, we were able to identify sufficient indications of response to suggest that frequency modulated acoustic signals periodically ramping either over the 50 Hz – 500 Hz range or the 1 kHz – 3 kHz range can trigger evasive reaction in the different species tested; a recommendation for future work would be to test a louder acoustic projector (in the order of 180 dB re µPa source level) capable of frequencies down to perhaps 100 or 200 Hz—as it may be technically difficult to achieve the desired acoustic levels at lower frequencies—and use either a composite sound pattern alternating lower-range and upper-range ramps or a single, wider range ramp from the lowest accessible frequency limit to 3 kHz. There is not enough experimental evidence from this study to confirm whether ramped signals, with progressive rises and abrupt drops in frequency, are or more or less effective than swept signals with progressive rises and falls.

The strobe light visual deterrent that we tested, despite its limited range, did cause an avoidance response in at least broad whitefish, inconnu and lake trout when operated at rates between four and eight pulses per second. A more powerful strobe light, possibly generating a mixed or modulated flash pattern between those two rates, would be a candidate for further tests. The fact remains, however, that a strobe light should be omni-directional to be useful as a field deployable deterrent, and the power output required for long-range effectiveness without the benefit of a concentrating reflector would have to be significantly higher. This fact, combined with the risk that suspended particles may strongly attenuate light propagation in lake waters—all the more appreciable considering that Dolomite Lake is one of the clearest in the Mackenzie Delta—, makes an acoustic deterrent our suggested option for further investigation.

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Appendix

Data Analysis Charts