THE USE OF A HIGH DEFINITION (HD) UNDERWATER CAMERA TO OBSERVE THE BEHAVIOUR OF YELLOWTAIL FLOUNDER (*Limanda ferruginea*) IN THE MOUTH OF A COMMERCIAL BOTTOM TRAWL

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The use of a high definition (HD) underwater camera to observe the behaviour of yellowtail flounder (*Limanda ferruginea*) in the mouth of a commercial bottom trawl

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Abstract

Underwater camera systems are often used to gain a better understanding of fish behaviour in relation to fishing gear prior to conducting gear modifications. Although the use of camera systems enables researchers to identify roundfish, their use has been unreliable in identifying flatfish to the species level. The high-definition self-contained underwater camera system developed in this study enabled flatfish to be identified to the species level with a high degree of certainty, something not previously capable of traditional camera systems. In this study, *in situ* underwater camera observations were conducted to observe and quantify the relationship between yellowtail flounder (*Limanda ferruginea*) behaviour and demersal trawls. A series of novel statistical tests were applied to evaluate hypotheses related to orientation, behaviour, residence time, and fate of an individual. These behavioural observations will form the basis for future trawl designs that incorporate improvements in catch efficiency and may reduce ecological impact.

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Co-authorship Statement

The author of this thesis designed the experiments, collected all of the data, analysed and wrote all the subsequent manuscripts. Dr. Paul D. Winger contributed significantly to the research proposal, experimental design, discussion of ideas, and provided editorial reviews of all chapters. George Legge contributed to the experimental design and provided editorial reviews of chapter 2. Dr. Stephen J. Walsh made substantial contributions to the research proposal, experimental design, and discussion of ideas of chapter 3. Dr. Walsh also provided editorial reviews to all chapters.

Dr. Paul D. Winger and George Legge are second and third authors of chapter 2. Chapter 2 (Underwood et al.) will be published in *The Journal of Ocean technology,* Volume 7.

Dr. Paul D. Winger and Dr. Stephen J. Walsh are second and third authors of chapter 3. Chapter 3 (Underwood et al.) will be submitted to *Fisheries Research* or a similar journal.

Chapter 1. Introduction and Overview

1.1 Newfoundland Yellowtail Flounder Industry

The yellowtail flounder (*Limanda ferruginea*; here after named yellowtail) fisheries, Northwest Atlantic Fisheries Organization (NAFO) Division 3LNO, on the Grand Bank off Newfoundland became commercially important in 1965 (1800 tons; Pitt, 1970) and by the early 1970s, the landing values had risen by 10-fold (Walsh et al., 2006; Maddock Parsons, 2009; Brodie et al., 2010). After these record highs, landings dropped significantly by the early 1990s and NAFO declared a moratorium on the fisheries in 1994. Due to the rapid improvements in the stock over the next 3 years, the fishery re-opened in August, 1998. Fishery Product International (FPI), a vertically integrated local company, operated the Newfoundland yellowtail industry up until 2007 when Ocean Choice International (OCI) purchased the majority share of the company. OCI, like FPI, has over 90% of the Canadian yellowtail and plaice fishery quota. Today, OCI operates a fleet of four 24-hour offshore factory stern trawlers (<50m) fishing annually on the Grand Bank from September to June (voluntary closure during spawning season). This small mouth pleuronectid is the only Grand Bank groundfish stock that has recovered after being placed under moratorium. This occurred when its relative biomass exceeded the precautionary reference level (B/Bmsy > 1, Fig 1.1; Brodie et al., 2010). In 2010, the recovered yellowtail stock of Grand Bank was the 3rd largest groundfish industry in Newfoundland (10,885 tons at 3.5 million dollars) and made up over half of all of Canada's total flatfish landings (DFO, 2010).

American plaice (*Hippoglossoides platessoides*; here after named plaice), a species often found in high concentrations with larger yellowtail, was also placed under a fisheries moratorium together with cod (*Gadus morhua*) and witch flounder (*Glyptocephalus cynoglossus*) during the mid 1990s and all are still under moratorium. As such, the Grand Bank yellowtail fishery has a strictly enforced plaice annual bycatch limit of 15% of its 16,500 ton quota. The industry uses a number of methods to reduce bycatch, including a larger codend mesh size than legally required and avoiding habitats of high concentrations of non-targeted species. However, avoidance of plaice commonly results in high catches of smaller, less valuable yellowtail (28 ~ 35cm; NAFO minimum legal size is 28cm), which are shipped to China for processing, taking valuable revenues from the Newfoundland economy. Avoidance of plaice also leads to increased fuel costs and loss of valuable fishing time while steaming in search of fishing grounds with fewer plaice. High catches of smaller marketable yellowtail further exasperates the problem, as they take longer to process while at sea. With the price of fuel increasing and bycatch restrictions on plaice and cod still in place, the efficiency and sustainability of the industry is of high importance to OCI, who now have Marine Stewardship Council certification for the yellowtail fishery and are investigating innovative trawling systems that are more species- and size- selective.

1.2 Fish Behaviour in Relation to Demersal Trawls

Fish reaction to demersal bottom trawls is commonly observed and interpreted in each of the three trawl path zones: 1) pre-trawl zone, ahead of the trawl doors, 2) herding zone, between the doors and the mouth of the trawl, and 3) capture zone, after entrance into the trawl (Fig. 1.2; Godø, 1994; Walsh, 1996; review by Winger et al., 2010a). In each zone fish are either a) in the trawl path (i.e., area between the wings of the trawl net) with a high chance of catchability, b) in the sweep path (i.e., area swept by the doors and ground wires) with a lower but still significant chance of catchability, or c) outside of the trawl and sweep path with a minimal chance of catchability. The remainder of this thesis will focus on zone 2 – fish behaviour between the doors and mouth of the trawl. For an in depth review of the entire capture process, please see earlier valuable reviews by Wardle (1983; 1986; 1993), Laevastu and Favorite (1988), Engås (1994), Godø (1994), Glass and Wardle (1995), and Winger et al. (2010a).

Roundfish such as cod and haddock (*Melanogrammus aeglefinis*) in zone 1 react visually to the doors and ground wires in a 'fountain manoeuvre' (Fig 1.3; Hall et al., 1986; Wardle, 1993). Keeping visual contact with the 'threat', individuals in the sweep path either swim into the trawl path (enter zone 2) and increase their chance of capture; or swim to the outside of the doors and escape. Once inside the doors (zone 2), individuals typically swim toward the trawl mouth keeping visual contact with the sand clouds and ground wires until the wings of the trawl come into sight. Here the 'fountain manoeuvre' occurs for a second time and depending on the position of the fish in relation to the sweep path, some individuals escape over or under the ground wires while others are herded closer to the trawl mouth (Wardle, 1993; Winger et al., 2010a). Roundfish have been found to swim in front of the mouth of the trawl, keeping pace with the trawl before either escaping between the footgear, rising over the top of the trawl or entering into the trawl (for example; Beamish, 1966; 1969; Main and Sangster, 1981; Main and Sangster, 1983). Several extrinsic and intrinsic factors are known (or suspected) to affect the expression of this behaviour, including ambient light intensity (Glass and Wardle, 1989; Walsh and Hickey, 1993), water temperature (Inoue et al., 1993; Winger, 2004), fish density (Godø et al., 1999; Jones et al., 2008), fish size (Walsh, 1992; Peake and Farrell, 2004), motivational state (Mohr, 1971; Skaret et al., 2005), physiological condition (Martínez et al., 2002; 2003) and previous experience with fishing gear (Hunter and Wisby, 1964; Brown and Warburton, 1999).

Flatfish, however behave very differently compared to roundfish. Flatfish tend to stop moving when they detect a 'threat' and react to the 'threat' after near-contact (Ryer, 2008), suggesting that avoidance behaviour in the pre-trawl zone (i.e., zone 1) may be minimal for flatfish. Main and Sangster (1981) described the herding of flatfish in zone 2 as seen in Figure 1.4 (see reviews by Ryer, 2008; Winger et al., 2010a). Individuals would react to the gear (doors, sand clouds, and ground wires) at a 90° degree angle, move away and either settle again inside zone 2 or be over taken by the gear and escape (Wardle, 1983; Ryer and Barnett, 2006). Flatfish require sufficient endurance to be herded into the trawl path and need to a) swim at a speed greater than the speed and angle of the gear, and b) maintain a distance in front of the gear. The individual's size, choice of gait (i.e., cruising, kick and gliding), and environmental conditions such as temperature, all affect endurance and the probability that a flatfish can be successfully herded (Winger et al., 1999; Winger, 2004). Smaller flatfish are often unable to maintain the speed needed to stay in front of the gear long enough to move into the trawl path, resulting in the gear overtaking them and the small flatfish escaping (Walsh, 1991). Small fish that are already close to the trawl path (i.e. first interact with the lower ground wires) have a shorter distance to move into the trawl path than those who interact with the doors, and therefore have a greater chance of successfully being herded. Large individuals generally have enough endurance to be herded into the trawl path. Flatfish tend to swim close to the seabed in the mouth of the trawl (Ryer and Barnett, 2006) and up to 5 m in front of the trawl (Walsh and Hickey, 1993; Albert et al., 2003; Winger et al., 2004). Residence time for flatfish is generally short (Main and Sangster, 1981), up to 18 s for Greenland halibut (Albert et al., 2003) and 2 - 12 s for flatfish in the northern Pacific (Bublitz, 1996), before they escape under the footgear or enter low into the trawl (Bublitz, 1996).

Understanding the differences in behaviours and morphology of coexisting species can lead to a more species- and size- specific trawl that will eliminate certain bycatch and target marketable sizes (He et al., 2008; Winger, 2008). While the observation and documentation of many commercial roundfish species behaviour has been extensive, the species level research on flatfish capture behaviour in demersal trawls has been limited due to the inability to identify species with certainty using underwater cameras (see research from Beamish, 1966; 1969; Walsh and Hickey, 1993; Bublitz, 1996; Kim and Wardle, 2003; Martinez et al., 2011); with the exception of Albert et al (2003) who were able to identify Greenland halibut (*Reinhardtius hippoglossoides*) using underwater cameras with lights.

1.3 Overview

The aim of this research was to first develop a camera system and methodology that can identify flatfish to the species level with high certainty, and then to use this system to explore the behaviour and the fate of yellowtail under commercial trawling conditions. This research is the first step towards developing innovative trawl designs capable of increased capture efficiency and reduced ecological impact (e.g., smaller, less valuable yellowtail and bycatch of plaice) for the Newfoundland flatfish commercial fishery.

My first experimental chapter (Chapter 2) outlines the development and evaluation of a new high definition (HD 1080i/720p) digital video system for observing fish behaviour in relation to fishing gear. Under laboratory conditions, the performance of the new system, as well as four similar camera systems used during the last decade, were compared. The new system and the best performing standard camera system were also compared at-sea by attaching them to the headline of an offshore groundfish trawl. Results showed that the current HD camera system out performed traditional camera systems. The chapter closes with a discussion on the benefits and limitations of upgrading existing camera systems to HD.

My second experimental chapter (Chapter 3) investigates the relationship between yellowtail behaviour and a commercial bottom trawl on the Grand Bank of Newfoundland. . The HD camera system, developed in chapter two, was used to observe individuals entering the mouth of the trawl and then later quantified using The Observer

XT 10.1 software. The main objective was to observe the individuals in the mouth of the trawl, just before the individual was caught or escaped). To observe their whole final herding behaviour, only individuals that were observed to rise out of the seafloor until they interacted with the trawl were included. A series of novel statistical tests were applied to evaluate hypotheses related to orientation, behaviour, residence time, and fate of an individual. Results showed after the initial reaction to the footgear, which was dependant on the orientation of the individual on or in the substrate, the behaviour of the individual in the trawl mouth dominated whether an individual fish was caught or escaped (behavioural dependent selectivity). The chapter closes with a discussion on the importance of fish behaviour on the capture process of demersal trawls.

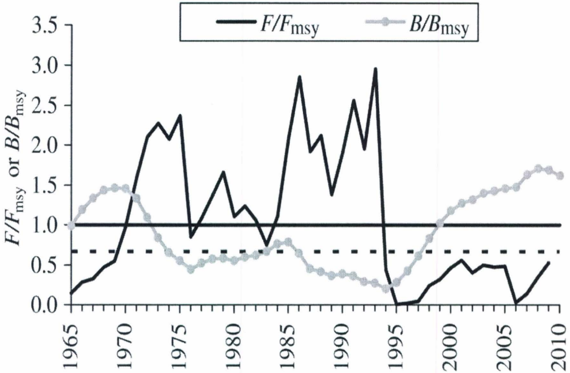

Figure 1.1 Relative biomass (biomass/ biomass maximum sustainable yield; B/B_{msy}) and relative fishing mortality (fishing mortality/ fishing mortality maximum sustainable yield; F/F_{msy}) estimates. The straight solid line indicates when B/B_{msy} or F/F_{msy} equals 1 and the dashed line indicates $F/F_{msy} = 0.67$. (Brodie et al., 2010)

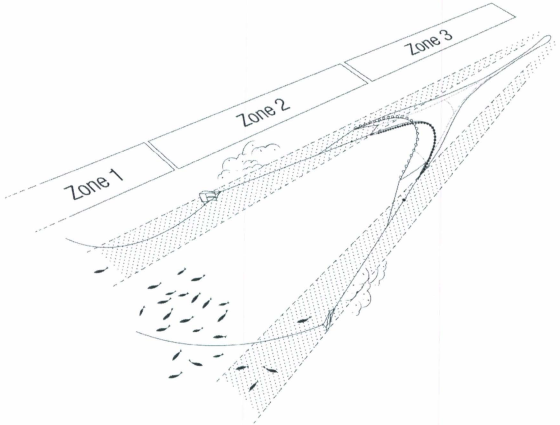

Figure 1.2 The three zones in the capture process. Pre-trawl zone (zone 1) is ahead of the trawl doors, the herding zone (zone 2) is from the doors to the mouth of the trawl and the capture zone (zone 3) is after an individual has entered the trawl. The doors and wires create the sweep path, indicated by the dotted area. Individuals between these two sweep paths have a high chance of being caught. Individuals in the sweep path have a lower but still significant chance of being caught (Winger et al., 2010a).

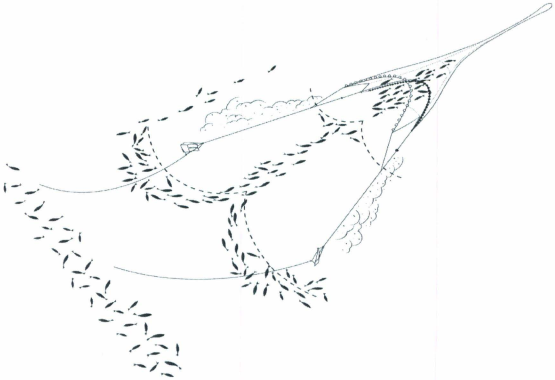

Figure 1.3 The 'fountain manoeuvre' of roundfish. The fish in front of the trawl have the potential of being herded and caught. Individuals in the sweep path will either turn around the doors into the trawl path or turn out and escape. Individuals that turned into the trawl path are herded into the mouth of the trawl. The dotted line indicates the point at which fish visually react, firstly to the doors and secondly to the mouth of the trawl (Winger et al., 2010a).

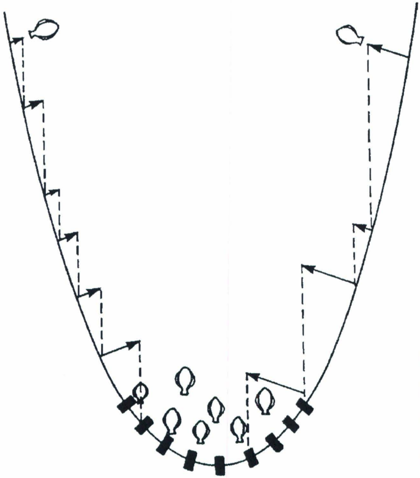

Figure 1.4 The behaviour of flatfish in the herding zone. Flatfish react to the ground wires at a 90° degree angle, moving away and settling again until they interact with the footgear (Winger et al., 2004).

Chapter 2. Out With the Old, In With the New: Development and Evaluation of a New High Definition (HD) Self-contained Underwater Camera System to Observe Fish and Fishing Gears *In Situ*.

2.1 Introduction

Commercial fisheries in many developed countries receive regular scrutiny and independent auditing to ensure sustainable harvesting practices are employed. Improvements in fishing gear technology have been widely adopted in an effort to reduce unintended ecological impacts associated with fishing activity. Significant research efforts have focused in particular on reducing bycatch (both observed and unobserved) during the past couple of decades (Graham, 2010). While traditional species resource surveys provide valuable information on abundance, distribution, and age composition; they often are not focused on providing information on fish behaviour in the capture process and using this information to understand or correct abundance indices. However in modifying or designing new fishing gear to be used for resource surveys and commercially, information on the behavioural interaction between the fish and the gear, e.g., where and how animals enter and escape from the fishing gear, and how other species in the herding zone affect these behaviours are both necessary and vital. In commercial operations, understanding the differences in behaviour and morphology of coexisting species can lead to improved fishing gear designs that are both species- and size- selective (e.g. Glass, 2000; He et al., 2008; Winger, 2008). For example, since the

1990's Atlantic cod (*Gadus morhua*) from a non-recovering stock off the eastern US was a bycatch issue for the region's haddock (*Melanogrammus aeglefinus*) fishery, leading to a closure of the industry in 2005 and 2007 (Federal Register, 2005, 2007). Based on previous camera observations at the entrance to the trawl (Main and Sangster, 1981; Wardle, 1993) cod were found to dive when encountering a trawl whereas haddock would rise, automatically separating the two species. These differences in behaviour lead to the design of the Eliminator trawl, targeting haddock over cod and therefore resolved the bycatch problem (Beutel et al., 2008).

Various methods have been developed to gain a better understanding of finfish and shellfish behaviour during the capture process by mobile and static fishing gears. These include direct observation by SCUBA divers, manned submersibles, towed underwater vehicles, hydroacoutics, high frequency sonars, acoustic telemetry, and perhaps the most common approach, self-contained underwater camera systems (see reviews by Urquhart and Stewart, 1993; Graham et al., 2004; Winger et al., 2010a). Depending on the fishery and application, these techniques can provide critical behavioural information needed to make informed decisions about fishing gear modification. Graham et al. (2004) described the recent advances in underwater camera systems used on demersal trawls and the types of cameras required in low light environments. Depending on the application and ocean light conditions, silicon-diode intensified target (SIT), charge-coupled cameras (CCD), and their intensified versions (ISIT and ICCD), can all be used with good success.

Due to the unique challenges that occur with observing fish behaviour in situ with cameras, for example attachment to mobile fishing gears, and the significantly lower light levels, researchers have had to trade-off image quality with the ability to see the subject. Camera resolution and pixel counts tend to be low in underwater cameras (320 – 700 horizontal lines, DeAlteris et al., 1992; Milliken et al., 1992; Bublitz, 1996; Olla et al., 2000; Albert et al., 2003; Yanase et al., 2009), limiting research on some individual species which have low contrast with their background, for example morphologically similar fish species such as flatfish. On rare occasions, observations can be made when a flatfish species is geographically isolated from other flatfish species (e.g. Godø et al., 1999). However, in most cases identification of flatfish to the species level has been difficult, forcing researchers to lump several species into a single 'flatfish' category (see research from Beamish, 1966; 1969; Walsh and Hickey, 1993; Bublitz, 1996; Kim and Wardle, 2003; Chosid et al., 2011), or drop a considerable number of observations because of uncertainty (e.g. Albert et al., 2003).

High definition (HD 1080i/720p) cameras are now widely used in both the film industry and consumer electronics. Due to their generally poor performance at low light intensities, their application in underwater use has been limited; however advances in recent years have opened up the opportunity to develop their potential use for studying fish behaviour and fishing gear (Favaro et al., 2011). The purpose of this study was to 1) develop a full HD camera system that could be easily mounted on a trawl during commercial operations and be capable of separating morphologically similar species in low contrast situations; 2) evaluate the camera system under laboratory conditions with previously used camera systems; and 3) to identify via video footage, yellowtail flounder

(*Limanda ferruginea*; here after named yellowtail) during commercial trawling operations.

2.2 Materials and Methods

2.2.1 Camera System and Operation

The new camera system was built upon the working principles of traditional self-contained underwater camera systems used in fishing gear research (e.g. Milliken et al., 1992; Legge, 1998; Olla et al., 2000). The basic system is separated into two parts; the instrument housing which contains the electronics; and the peripherals, which include the camera head and lighting fixture (Fig. 2.1). An interchangeable umbilical allows for different camera heads and lights to work with the same electronics set-up. Inside the housing, the inner frame consists of a relay system (Potter & Brumfield CNT Series) and two 12-volt batteries. The original system used a standard definition (SD) Kongsberg Osprey CCD camera head and a Hi8 Sony CCD-TR81 8 mm camcorder for recording video. The new system incorporates a HD Splashcam Seatrex camera head, nanoFlash HD/SD recorder (convergent-design.com), and an AJA HD10C2 HD-SDI to analog HD converter (www.aja.com).

The relay system delays the start of recording and cuts the power to the electronics after the assigned time. The converter can be used with both the SD and HD, allowing multiple kinds of cameras to be used. The nanoFlash records up to 280 mbps and identifies the correct mbps needed by the video source. The nanoFlash records digitally onto two 64Gb compact flash disks allowing 164 minutes at the highest mbps. An internal clock allows you to synchronize the video's time stamp with other on board instrumentation such as hydroacoustic gear monitoring sensors. The focus and mode of the camera head is controlled by external software via a RS-232 connection.

The camera head and lighting fixture are mounted in a protective cage (53.0 x 53.0 x 28.5 cm aluminum frame) with a multi-angle camera mount enabling the camera to be rotated 360 degrees, angled every 10 degrees (± 3 degrees) depending on the desired field of view. Lighting fixtures can also be mounted in the cage if needed. The cage is masked with black tape to reduce light reflection on the camera lens.

2.2.2 Lab Trials

Controlled evaluations of the old and new camera systems were conducted in September 2010 at the Fisheries and Marine Institute's 22 m long flume tank in St. John's (see Winger et al., 2006 for more details). A 3.0 m long Camera Resolution and Imagery Board (CRIB) adapted from the 1951 USAF resolution test chart (Department of Defense, 1959) was developed, consisting of a total of 72 bars ranging in width from 0.1 to 8.0 cm with each width repeated 3 times (Fig. 2.2). The CRIB was used to compare the quality of the footage from 5 different combinations of cameras and recording devices. These included a standard definition camera and two moving state (i.e., tape based) recording devices (Hi8 and MiniDV); standard definition camera and two solid state recording devices (SD and HD); and the high definition camera with the high definition solid state recording device (Table 2.1). While the intent of this comparison was not to include all brands of products available on the market, it was however meant to be representative of the typical equipment used in this field of research.

Each experimental setup involved placing the respective camera underwater at a distance of 4.0 m vertically above the CRIB and recording the footage onto one of the recording devices. Care was taken to standardize the setup as well as minimize variation in environmental conditions such as ambient light level, shadows, and water clarity. Four frames were randomly captured from each experimental setup. The total number of bars observed and the thinnest group of bars (all bars of the same width that could be identified) were recorded. One-way Analysis of Variance (ANOVA) was used to compare differences in bars observed between camera systems followed by Tukey's honestly significant different (HSD) test for all-pairwise comparisons ($p = 0.05$).

2.2.3 Field Trials

Sea trials were conducted onboard the commercial Ocean Choice International (OCI) groundfish trawler, *F/V Aqviq,* on the southern part of the Grand Bank off eastern Newfoundland in May and June 2010. The system was evaluated using both the SD Kongsberg Osprey CCD camera head and the HD Splashcam Seatrex camera head, both installed in the protective cage with the video signal transferred via the umbilical to the recording housing where data were recorded onto the nanoFlash digital video recorder. Five successful tows were completed in May using the SD Kongsberg Osprey CCD camera, placing the cage and camera on the a) trawl's headline looking toward the lower belly and footgear, b) on the wing looking across the mouth of the trawl to the other wing, and c) straight down at the footgear. In June, five additional tows were completed with the HD Splashcam Seatrex camera, where it was placed only on the trawl's headline looking directly down at the footgear. In all cases, the camera systems were placed on the first tow of the afternoon (i.e. 12:00 – 15:00) in depths of 60 – 80 m to optimize the natural light.

Prior to mounting the camera on the trawl, the instrument housing was opened and the batteries were connected. At this time there was power to the camera head and the relay only. The camera was set to the infinite focus, 280 mbps (allowing a recording time of 164 min) and ICR (Infrared Cut-Filter) mode. The relays were set to the required start and stop times. The electronics were then placed into the recording housing and it was sealed. The camera head was secured inside the protective cage to prevent collision and damage. The recording housing containing the electronics was secured to the trawl in a tightly fitting bag made of polyethylene netting, 1.5 m from the camera and its protective cage. Four 20.3 cm diameter trawl floats were tied to the cage and housing to achieve neutral buoyancy and avoid any negative effect on the geometry of the trawl.

Analysis of the video footage was later conducted at the laboratory using Noldus Information Technology, Observer XT 10.1 software (www.noldus.com), and viewed on an HD 1080p monitor. The footage was divided into a grid of 100 squares in the manner similar to Albert et al. (2003). Only footage looking at the footgear from the headline was used to determine identification. A grid square was selected from a list of randomly generated numbers and while the footage was playing, the first individual fish in that square observed rising from the seafloor until the individual interacted with the trawl was used. After the observation (when the individual interacted with the trawl) the next grid square was selected from the list of randomly generated numbers and the process was repeated until the footage ended or it was impossible to identify individuals on or in the substrate from the video. Individuals were categorised as yellowtail (identified by their fleshy lips and small mouth; Collette and Klein-MacPhee, 2002) or unidentified.

2.3 Results and Discussion

2.3.1 Camera System and Operation

The original camera system, using a Hi8 camcorder, consisted of moving parts (Hi8 tapes, tape tracks). The underwater environment in which this camera system was used is not entirely compatible with this type of technology. While deploying the system, the recording housing can often come into contact with the stern of the vessel (Underwood, personal observations) causing any components inside the system to be bumped (Legge, personal communications). The high definition camera system developed in this study uses a recording device that is solid state, using a memory card rather than a tape to digitally record the observations. Solid state reduces the chance of the recording device stopping unexpectedly when bumped and eliminates the requirement to 'digitize' footage upon return to the laboratory.

Upon initial powering, many underwater cameras are set to auto-focus as the default setting by the manufacturers. In underwater environments, this feature can cause the camera to routinely go out of focus as it tries to focus on particles in the water column moving between the fishing gear and the camera. Out of focus footage increases the difficulty in identifying individual fish, requiring extended time at sea to compensate for the loss in usable footage. In contrast, the focus of the HD Splashcam Seatrex camera used in this study was ideal given that it could be set to infinite prior to deployment, thus stopping the camera from focusing solely on particles in the water and increasing the probability of getting valuable footage.

2.3.2 Lab Trials

Analysis of the flume tank video recordings of the CRIB showed variations in performance level among the 5 camera systems evaluated ($F_{[4,15]} = 140.898$, $p < 0.001$). The number of bars observed increased as the camera system improved in technology (Fig. 2.3). The original system (standard definition Kongsberg Osprey CCD camera with a Hi8 recording device) observed an average of 68% of the bars (49 out of 72 bars). Using the same standard definition (SD) camera with a newer recording device (MiniDV) produced a modest improvement in the percentage of bars observed (71%; 51 out of 72 bars) but this difference was not statistically significant ($p > 0.05$; Table 2.2). The conversion to digital solid state recording devices significantly improved image quality to 79% of bars observed (56.75 out of 72 bars; $p < 0.05$), however the use of a SD or HD solid state recording device did not significantly influence image quality (79% for both, *p*

> 0.05). The HD camera system significantly outperformed the other camera systems and was the only camera system to observe over 80% of the bars (89%; 64 out of 72 bars). The high definition camera with the HD digital solid state recording device observed 10% more bars than the SD camera with either of the solid state recording devices (89% and 79% respectively; $p < 0.05$) and over 20% more bars than the original system (89% and 68% respectively; $p < 0.05$).

The minimum bar width observed also improved with the camera technology (Fig. 2.4). The original camera system (SD + Hi8) as well as its immediate successor (SD + MiniDV) were able to detect bar widths of 0.9 cm whereas the solid state recording devices with the same camera were able to detect smaller widths (SD solid state recording device = 0.7 cm; HD recording device = 0.6 cm). The high definition camera system (HD + HD) by comparison was consistently able to detect bar widths of 0.4 cm, outperforming all other systems. However these results occurred under optimum conditions and were not subjected to low light levels and moving water as found in underwater environments. Even with the challenges of real time footage, it is expected that the high definition camera system should out perform the original camera system and that using a solid state recording device would be an improvement, for in situ measurements of fish and fishing gears.

2.3.3 Field Trials

Noticeable differences in image quality were observed among the video camera systems when mounted on the headline of a bottom trawl (Fig. 2.5). Frame A shows a still frame from video collected using the SD Kongsberg Osprey CCD camera and Hi8 recording device (SD + Hi8) collected more than a decade ago (Legge, 1998). Frame B and C show still frames collected during this study, including the same SD Kongsberg Osprey CCD camera connected to the HD solid state recording device (SD + HD; Frame B), and finally the HD Splashcam Seatrex camera connected to the HD solid state recording device (HD + HD; Frame C). Caution is advised when comparing the frames as the images were collected from different tows and in one case a different year (i.e., Frame A). Nonetheless, the comparison illustrates the evolution in image quality with technological improvements over time and supports the empirical observations from the lab trials (see above). In the preliminary behavioural studies (see chapter 3), successful identification of yellowtail (to the species level) was accomplished 72% of the time (72 out of 100 fish) when using footage from the HD solid state camera system compared to only 46% of the time (23 out of 50 fish) when using footage from the SD solid state camera system, representing a significant improvement in underwater camera systems. A small amount of observations were recorded for the SD solid state camera system because only 50 individuals were observed rising from the seafloor due to footage being out of focus.

As a result of these improvements, high definition (HD) cameras can now be used in the field of fish capture research due to technical advances in their minimum illumination levels. Several of the more common types of self-contained underwater camera systems (as used in Castro et al., 1992; Weinberg and Munro, 1999; Albert et al., 2003) have lower minimum illumination levels than the high definition camera system described here, and are currently better alternatives for very low light environments and night observations (Fig. 2.6). It is anticipated that in the next few years the technological improvements seen in CCD cameras from 1993-2004 (Graham et al., 2004; Fig. 6), such as increasing minimum illumination levels from 1 lux (the same as the high definition camera) to 10^{-4} lux, will also occur in HD camera systems. However, until these developments occur and permit high definition technology to be used in very low light observations, current high definition camera systems will still require independent illumination for dark underwater environments.

Table 2.1 Description of the original and new experimental camera systems evaluated under laboratory conditions in the Marine Institute flume tank. Kongsberg is the Kongsberg OE 1367 CCD model and Splashcam is the Splashcam SeaTrex HD.

Set-up	Pixel size	Camera	Converter	Recording Device	Recording Device Model
Original	640x480	Kongsberg	none	Hi8 Handycam	Sony CCD-TR81
Experimental 1	640x480	Kongsberg	none	MiniDV Handycam	Sony DCR-HC42
Experimental 2	640x480	Kongsberg	none	SD digital solid state	µAVR H.264x4
Experimental 3	1280x720	Kongsberg	AJA HD10C2	HD digital solid state	Convergent Design nanoFlash
Experimental 4	1280x720	Splashcam	AJA HD10C2	HD digital solid state	Convergent Design nanoFlash

Table 2.2 Paired comparisons of the mean number of bars detected by the different camera systems. The values indicate the difference between two compared means ($\mu 1 - \mu 2$).

	Hi8	MiniDV	SD + SD	SD + HD
MiniDV	2.00			
SD + SD	7.75*	5.75*		
SD + HD	8.00*	6.00*	0.25	
HD + HD	15.00*	13.00*	7.75*	7.00*

* significant difference (Tukey test, $p < 0.05$)

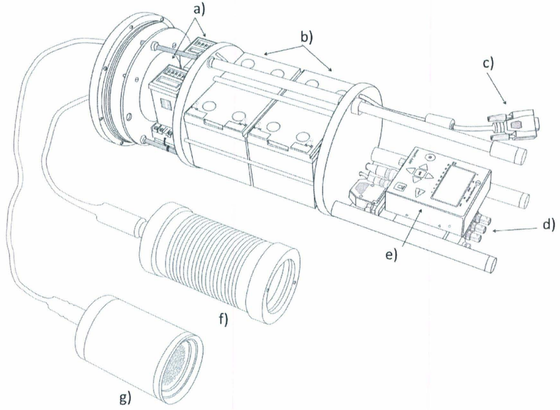

Figure 2.1 The individual components of the high definition (HD) self-contained underwater camera system developed at the Fisheries and Marine Institute of Memorial University. The inside of the instrument housing (depth-rated to 1500m) consists of a) the programmable relay system; b) two 12-volt batteries; c) RS-232 connection; d) SD/HD converter and e) a nanoFlash digital recorder. Also illustrated are f) the HD Splashcam Seatrex camera head; and g) the interchangeable LED lights (red, infrared and white).

Figure 2.2 The Camera Resolution and Imagery Board (CRIB) adapted from the 1951 USAF resolution test chart (Department of Defense, 1959), consisting of 72 black bars ranging in width from 0.1 – 8.0 cm to test the image quality of the underwater camera systems.

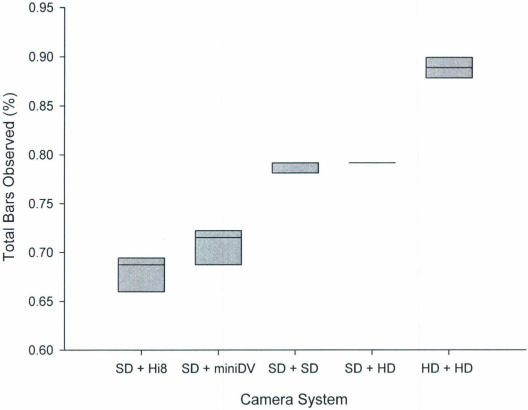

Figure 2.3 The median percentage of total bars observed (out of 72) for the 4 frames of each camera system (camera + recording device). The five camera systems include, the standard definition (SD) camera and a Hi8 recording device, SD camera and a MiniDV recording device, SD camera and a SD solid state recording device, a SD camera and a high definition (HD) solid state recording device, and a HD camera plus a HD solid state recording device. The boxes represent the range of percentages observed, with the median indicated by a black line.

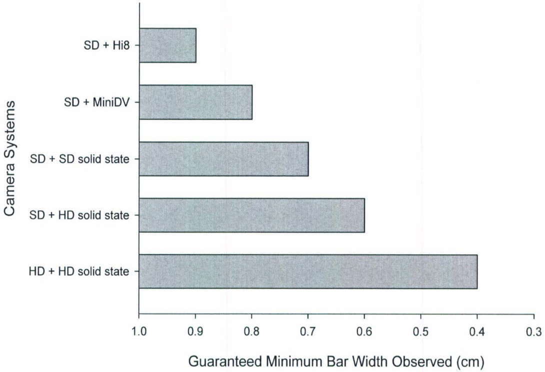

Figure 2.4 Guaranteed minimum bar widths (all frames observed three bars) each camera system observed when the CRIB was 4.0 m underwater from the camera. The five camera systems include, the standard definition (SD) camera and a Hi8 recording device, SD camera and a MiniDV recording device, SD camera and a SD solid state recording device, a SD camera and a high definition (HD) solid state recording device, and a HD camera plus a HD solid state recording device.

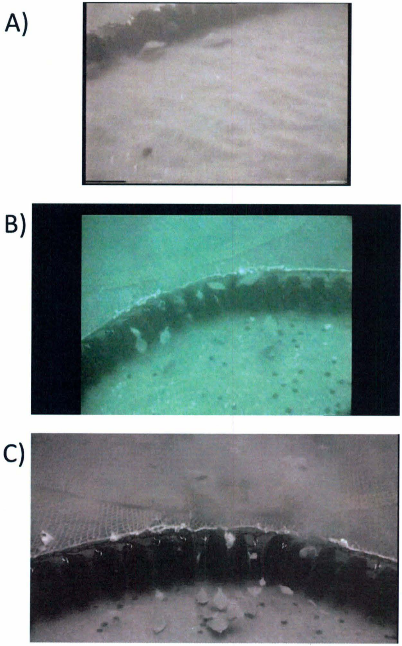

Figure 2.5 Still frames collected from three different camera systems used on the Grand Banks of Newfoundland. Frame A was collected from the SD camera and Hi8 recording device in 1998 (Legge 1998). Frame B was from the SD camera and Frame C from the new HD camera, both recorded using the HD recording device in 2010.

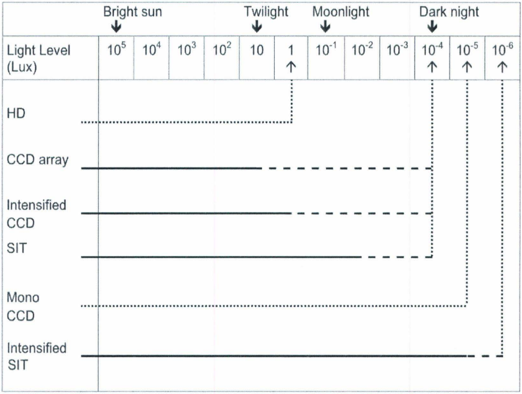

Figure 2.6 Minimum illumination levels for various camera types. Updated from Graham et al. (2004) to include high definition cameras. The solid lines are the camera minimum illumination in 1993; dashed lines indicate minimum illumination in 2004 and the dotted lines indicate the current minimum illumination.

Chapter 3. If Nemo Was a Flatfish… Would He 'Just Keep Swimming?': Behaviour of Yellowtail Flounder (*Limanda ferruginea*) In the Mouth of a Commercial Bottom Trawl.

3.1 Introduction

In recent years, demersal trawl fisheries in developed countries have moved toward more sustainable harvesting practices, which include among other things, the avoidance of areas with high concentrations of non-targeted species and modification to bottom trawl designs to be more species- and size- selective (see review by Graham, 2010). With the advancements in technology, underwater camera systems are now commonly used as part of the fishing gear development cycle to observe fish capture behaviour as a means of separating bycatch and targeted species during the harvesting process (Winger et al., 2006; He et al., 2008). In many cases, the behaviour of roundfish has been documented to the individual species level (Beamish, 1966; 1969; Main and Sangster, 1983; Beutel et al., 2008; He et al., 2008) whereas the behaviour of flatfish tends to be grouped together due to the inability to identify species with certainty using underwater cameras (see research from Beamish, 1966; 1969; Walsh and Hickey, 1993; Bublitz, 1996; Kim and Wardle, 2003; Chosid et al., 2011). One exception is that of Albert et al. (2003) who were able to identify Greenland halibut (*Reinhardtius hippoglossoides*) with the use of underwater cameras and lights.

The evolution of previous studies on fish behaviour in relation to bottom trawls have moved from an in-depth qualitative description of the behaviour (see for example: Main and Sangster, 1981; Main and Sangster, 1983; Godø et al., 1999) to quantifying the behaviour by percentage (Walsh and Hickey, 1993). While, attempts at mathematical modelling of fish behaviour related to trawling operations has been used throughout the evolution of previous studies (Foster, 1969; Dickson, 1993a; 1993b; Kim and Wardle, 2003), the absence of rigorous statistical treatment of trawl induced fish behaviour studies has been noteworthy.

Flatfish studies have observed density, size and species selectivity in the herding zone (Walsh, 1992; Godø et al., 1999). However, once the individual is in the trawl path and reacting to the footgear, it is unclear what factor or factors are more important in the footgear selectivity (if an individual escaped or was caught). This study concentrated on the fish capture process of yellowtail flounder (*Limanda ferruginea*; here after named yellowtail) in the mouth of the trawl with the following objectives; 1) to document any evidence of previous herding and the effects of herding on an individual's behaviour, 2) quantify trawl-induced behaviour, 3) calculate the residence time of yellowtail, and 4) investigate if density and size are main factors (i.e. when modelled with substrate type, individual behaviour, and gait) in footgear selectivity. Such background knowledge is needed when designing new species- and size- specific bottom trawls for the Newfoundland flatfish fishery.

3.2 Methods and Materials

To adequately document and investigate the behaviour of yellowtail in the mouth of a bottom trawl, a new high definition (HD) self-contained underwater camera system was developed (see chapter 2 for more information). The system was built upon the working principles of traditional self-contained underwater camera systems used in fishing gear research (e.g. Milliken et al., 1992; Legge, 1998; Olla et al., 2000), but with added improvements in image quality and digital recording. Previous research has indicated mixed reviews on the effects of lights in behavioural studies (Glass and Wardle, 1989; Walsh and Hickey, 1993; Weinberg and Munro, 1999) and therefore artificial lights were not used with the current camera system to reduce potential behavioural variation from the lights. *In situ* observations were conducted onboard the Ocean Choice International (OCI) groundfish trawler, *F/V Aqviq*, on the southern section of the Grand Bank off eastern Newfoundland in June 2010 (Fig. 3.1). The camera system was placed on the headline of a 2-bridle, 2-seam bottom trawl known as the Goldentop (Fig. 3.2) such that the field of view covered the first lower belly and the midsection of the footgear (52.5 cm rockhopper rubber discs with 20 cm spacers) as shown in Figure 3.3. Observations of flatfish from five fishing tows (over 12 hours of footage) were collected at depths of approximately 65 – 85 m with bottom temperatures ranging from 0.6 – 1.2 C. Towing speeds varied from 1.5 – 1.7 m s^{-1} (average of 3 knots) and tow durations varied from 2 – 3 hrs. The first tow of each afternoon was used for each video to optimize the natural underwater light. Catch percentages of flatfish varied with each tow, ranging from 84 – 92% for yellowtail and 8 – 15% for American plaice (*Hippoglossoides platessoides*; here after named plaice) (Table 3.1). Witch flounder (*Glyptocephalus cynoglossus*) was present in one tow.

Analysis of the video footage was later conducted in the laboratory using Noldus Information Technology, Observer XT 10.1 software (www.noldus.com). The footage was divided into a grid of 100 squares on an HD 1080p monitor (Fig. 3.4) in the manner similar to Albert et al. (2003). A grid square was selected from a list of randomly generated numbers and while the footage was playing, the behaviour sequence of the first individual fish in that square observed rising from the seabed until it either entered the net or passed underneath the footgear was used. After that sequence was finished the next grid square was selected from the list of randomly generated numbers and the process was repeated until the footage ended or it was impossible to identify individuals on or in the substrate from the video. The behavioural sequence of 190 individuals was included in the analysis.

Eight behavioural variables were coded for each fish according to pre-determined categories (Table 3.2) in the manner similar to previous behavioural studies of this type (e.g., Walsh and Hickey, 1993; Albert et al., 2003; Piasente et al., 2004). The eight behavioural variables recorded were: species, length, substrate type, orientation on or in the substrate, gait, start trawl mouth behaviour, end trawl mouth behaviour, and trawl interaction; with each observation coded into a eight digit number. Individuals were categorised as yellowtail (identified by their fleshy lips and small mouth; Collette and Klein-MacPhee, 2002) or unidentified. Fish length was estimated based on the known dimensions of footgear components (one rockhopper disc and spacer was 30 cm) within the field of view. Individuals were estimated as larger or smaller than 30 cm, the reference length, at the time the individual was closest to the footgear. Individuals unable to be classified by length using this manner were grouped as 'unidentified.' The orientation of the individual on or in the substrate was recorded at the start of the observation (before the individual rose from the seabed). After leaving the seabed, swimming behaviour was classified into six categories (Trawl Mouth Behaviours; Table 3.2). Many individuals exhibited a second trawl mouth behaviour following the initial swimming reaction after being disturbed (herded) from the seabed. Both an individual's start and end behaviour were combined to describe the trawl mouth behaviour sequence. I modelled the footgear selectivity of individual fish as a binomial variable (caught or escaped). The fate of each individual (escaped or captured) was further separated into six trawl interactions (Table 3.2).

In addition to the eight variables mentioned above, residence time, start and end density of flatfish, and location of an individual in relation to the footgear were estimated. The time, in seconds, from when an individual rose from the seabed until it passed over or under the footgear was recorded as the residence time (sometimes referred to as endurance in the literature). Flatfish densities (estimated number of flatfish in the video frame, including unidentified flatfish species) were recorded at the start (start density) and end (end density) of each observation. Location of an individual in relation to the footgear was recorded at the start of the observation and was categorized into three groups. Individuals rising from the seabed within 2 squares either side of the centre of the footgear were categorized as in the 'middle' of the trawl path. Individuals rising from the seabed greater than 2 squares to the port side or starboard side of the footgear were classified as 'port' and 'starboard' respectively (Fig. 3.4).

3.2.1 Hypothesis Testing

Four hypotheses were evaluated in this study. The first hypothesis, to determine if the orientation of yellowtail on or in the substrate was dependent on their location in the mouth of the trawl or their start trawl mouth behaviour, the orientation was tested for uniformity (randomness) with the Rayleigh test using Oriana version 3.0. Secondly, to determine if the start trawl mouth behaviour of a yellowtail was dependent on fish length, start density, or substrate type, a multinomial logistic regression model (MLR) was carried out using SPSS version 17.0. Thirdly, to determine if the residence time of a yellowtail was dependent on fish length, start density, substrate type, gait, or start trawl mouth behaviour, a General Linear Model (GLM) approach was carried out using R version 2.12. Fourthly, to determine if the footgear selectivity of yellowtail was dependent on fish length, end density, substrate type, gait, or end behaviour, a Generalized Linear Model (GzLM) with binomial error and was carried out using R version 2.12 to statistically test the hypothesis. To graphically represent the fate of an individual, multiple correspondence analysis plots were used. All models with the predictor variable 'length' had the sample size reduced to 150 individuals, i.e. the 'unidentified' length sub-category was removed.

3.3 Results

3.3.1 Orientation Hypothesis

Orientation of yellowtail on or in the substrate varied depending on which side of the trawl mouth the individual was originally observed (Fig. 3.5) and was found to be non-random, i.e., significantly clustered, for each of the three categories ($p < 0.001$, Table 3.3a). Individuals on the port side of the trawl mouth were mainly (53%) oriented in a direction facing toward the middle of the trawl path, area between the wings of the trawl net (i.e., starboard ± 45°; Fig. 3.5a). Individuals on the starboard side were similarly (59%) oriented toward the trawl path (i.e., port ± 45°; Fig. 3.5b). However, individuals in the middle of the trawl mouth showed no obvious directional pattern, other than away from the immediate threat of the trawl behind them (i.e. facing in all directions away from the trawl; Fig. 3.5c). Start behaviour (initial behaviour upon rising from the seabed) seemed to be dependent on the orientation of the individual on or in the substrate (Fig. 3.6). Individuals who started swimming across the trawl path (Fig. 3.6a) were 87% of the time, already orientated in that direction (Swim Across; ± 45°; $p < 0.001$, Table 3.3b). Individuals who rose horizontally (Horizontal Rise; $p < 0.001$, Table 3.3b) or swam close to the seabed (Swim near Seabed; $p < 0.001$, Table 3.3b) were over 95% of the time facing the vessel (± 45°; Fig. 3.5b-c). On the other hand, individuals who rose vertically from the seabed displayed no preference to orientation (Rise Vertically; $p = 0.137$, Table 3.3b; Fig. 3.6d).

3.3.2 *Trawl Mouth Behaviour Hypothesis*

Four of the six trawl mouth behaviours of yellowtail (Table 3.2) were observed as primary behaviours upon rising from the seabed (Fig. 3.7a). Out of the potential 36 combinations of the six start and end behaviours which formed a trawl mouth sequence, 11 trawl mouth sequences were observed (Fig. 3.7d) with 57% of yellowtail changing their behaviour in response to herding during the sequence. Most yellowtail (59%) initially swam across the trawl path with over half of those individuals changing their swimming behaviour. A third (31%) of yellowtail initially swam close to the seabed, of which over 78% of those, changed their swimming behaviour during the trawl mouth sequence. Only 4% of individuals initially swam horizontally, of which 67% of them changed their behaviour to rise vertically. Individuals that initially rose vertically (6%) never changed their behaviour. The MLR (Model 2) results showed that none of the predictor variables (fish length, start density and substrate type) were important in explaining the variation in the start trawl mouth behaviour of yellowtail ($p > 0.05$; Table 3.4a).

The trawl mouth behaviour sequences (start and end behaviours combined) of yellowtail were unable to be statistically analysed due to the limited sample size. However, quantitative data suggests a difference in the trawl mouth sequences employed by large and small individuals (Fig. 3.7e-f). Small individuals who were observed initially swimming near the seabed more often stayed close to the seabed than large individuals (28% and 18%, respectively). Large individuals were more likely to change from swimming near the seabed to swimming across the trawl mouth (>50%; Fig. 3.7e-f). A quarter (25%) of small individuals that initially rose horizontally away from the seabed when disturbed changed their swimming behaviour to rise vertically (Fig. 3.7e) whereas 50% of large individuals that rose horizontally changed their behaviour to rise vertically (Fig. 3.7f).

3.3.3 Residence Time Hypothesis

Residence time for yellowtail swimming in the trawl mouth varied from 0.8 – 31.9 s with a mean of 3.9 ± SE 0.30 s (Table 3.5). The assumptions of homogenous and independence of residuals in Model 1 were not met (Table 3.4b) so Model 1 was randomized, i.e. reordering observed data values, to remove the assumptions (Manly, 2007) with 5000 replicas as recommended by Adams and Anthony (1996) (Table 3.4c). The predictor variables fish length, start density, substrate type, and gait type were not important in explaining variation in residence times (n=150; $p > 0.05$) (Model 1, Table 3.4c). The only significant predictor variable important in explaining variation in residence times was the start trawl mouth behaviours ($p < 0.05$, Table 3.4c). Vertical rise behaviour had the shortest residence time of 1.1 ± SE 0.09 s while swimming near the seabed behaviour had the longest residence time of 4.6 ± SE 0.76 s (Table 3.5).

3.3.4 Selectivity Hypothesis

Escapement of individual yellowtail under the trawl footgear was observed in 37% of the

150 observations (Table 3.6). The assumption for normal residuals in Model 3 (Table 3.4d) was not met and therefore Model 3 was randomized with 5,000 replicas (Table 3.4e). The predicted variables, fish length, end density, and substrate type were not important in explaining the variation in trawl mouth selection of individual fish ($p > 0.05$; Model 3,Table 3.4e). However, end behaviour and gait were significant in explaining variation in the fate (escape or capture) of an individual ($p < 0.05$; Table 3.4e). All of those individuals (100%) that ended their trawl mouth sequence (Fig. 3.8d) swimming near the seabed escaped, compared to those individuals that rose horizontally or vertically who almost always were caught (3% and 0% escaped, respectively; Table 3.6). Although rare, one individual even rose vertically and escaped between the bolsch line and the rockhopper chain of the footgear, accounting for the 3% of escapement. Individuals choosing to swim across the trawl path as their end behaviour were just as likely to escape or be captured (54% and 46%, respectively). When the fate of an individual was examined in relation to their physical contact with the trawl (overtaken, collide, seeking escapement, or entering the trawl; Table 3.2) the choice of their end behaviour was important to the final outcome (Fig. 3.8b,d). Individuals swimming near the seabed were more likely to be overtaken by the footgear (55%; Table 3.6) than to collide with the gear or actively escape. Most individuals (92%) that swam across the trawl mouth actively escaped (49%), or actively swam into the trawl (43% actively caught; Table 3.6). Individuals that rose horizontally either actively swam into the trawl (47%) or were overtaken by the trawl and caught (50%), whereas 79% of individuals that rose vertically actively swam into the trawl. A small percent (2%) of all yellowtail collided with the footgear and escaped (Table 3.6; Figure 3.8e).

3.4 Discussion

This study concentrated on the behaviour of yellowtail at the mouth of the trawl. I was unable to investigate the behaviour prior to this area or once the individuals past the footgear. However, previous studies have investigated these areas and so I draw from these studies to support my findings. Flatfish are commonly herded perpendicular to the ground wires, trawl bridles and footgear for short distances before they settle down on the seabed. This 'swim then settle' behaviour can occur multiple times throughout the herding process (Main and Sangster, 1981; Wardle, 1983; Ryer, 2008; Winger et al., 2010a). They appear to respond to a bottom trawl in a manner analogous to a predator-prey interaction (Ryer and Barnett, 2006; Ryer, 2008), Such an anti-predator strategy would explain the on-bottom orientations I observed on the port and starboard side of the trawl as having been from yellowtail previously herded either in or ahead of the trawl mouth. Greenland halibut also showed similar orientations (Albert et al. 2003) but to a lesser extent then yellowtail, however, the amount of observations on orientations was much lower than this study. Random orientations of yellowtail in the bosum section (middle) of the footgear appear to be a common herding response in many flatfish (Walsh and Hickey 1993; Albert et al. 2003). I hypothesized that the start behavioural response (herding) of flatfish is a function of the direction they are orientated on or in the substrate. Flatfish responses seem to be limited to either moving away from the herding stimuli in a straight line or rising vertically to rapidly avoid the stimuli. Hemmings (1973) and Stickney et al. (1973) also observed flatfish moving away from the herding stimuli in a straight line, with Stickney et al. (1973) concluding that the responses are due to the morphology of flatfish.

This start take off swimming behaviour response to the approaching footgear was not significantly influenced by length, start density, or substrate. Beamish (1966; 1969) observed over half of flatfish (winter flounder (*Pseudopleuronectes americanus*) and American plaice (*Hippoglossoides platessoides*)) swimming toward the trawl wings, and Walsh and Hickey (1993) also observed similar start behaviour movements across the trawl path. However, 57% of yellowtail then changed their start swimming behaviour, i.e. their first reaction was to swim in the direction they were facing and then changed behaviour while swimming. The cost of continuing one's behaviour changes over time and if the cost increases, there is a drive for the animal to switch behaviours (Winger et al. 2010a; Ydenberg and Dill 1986). It is believed that the cost of staying in the initial swimming behaviour would have resulted in yellowtail interacting with the threat, in this case, the footgear and therefore the change in swimming behaviour occurred. These swimming behavioural changes are manifestations of the strong antipredator strategy and, unfortunately, due to small sample sizes, the whole trawl mouth behaviour (start and end behaviours combined) was unable to be analysed together.

The different start behavioural responses of yellowtail had a significant impact on the individual's residence time (residence time hypothesis) and the selectivity of the footgear (selectivity hypothesis). The residence times ranged from 1 to 40 s and are comparable to published residence times for flatfish: up to 18 s for Greenland halibut (Albert et al.,

2003) and 2 - 12 s for flatfish in the northern Pacific (Bublitz, 1996). However all reported residence times were significantly lower than the upper range of 60 s reported by Main and Sangster (1981) for flatfish off Scotland. This study was able to accurately quantify the residence times of yellowtail to a tenth of a second and the discrepancy may simply be due to not having the sophisticated cameras and software that are available today. What is striking about the residence times is that individuals choosing the vertical rise behaviour, to rapidly avoid the trawl did so in 1 s on average while those individuals who choose to swim near the substrate had the longest average residence time at 5 s. Flatfish swimming within one body length of the substrate, will experience less drag and require less energy to move away from the threat (Videler, 1993; Webb and Gerstner, 2000) than those swimming vertically. In the current study, I observed that neither fish length, start density, substrate type, nor gait choice, significantly explained variation in residence time. However, some of these predictor variables have had significant effects on flatfish swimming capabilities in the literature. Laboratory studies investigating the swimming capability of flatfish have reported both length-dependent swimming endurance (Winger et al., 1999) and length-dependent gait use (Winger et al., 2004).. These laboratory studies were conducted at low swimming speeds (~0.3 m s^{-1}), comparable to the herding speeds of trawl bridles, however, these relationships may not have held if they were conducted at the higher velocities (~1.5 m s^{-1}) experienced by individuals swimming in the trawl mouth. In terms of gait, Peake and Farrell (2006) and Breen et al. (2004) suggested that fish may behaviourally choose to stop swimming rather than to succumb to exhaustion, when there was a change in threat assessment. From the camera position on the trawl's headline I did not observe if yellowtail continued to swim inside the trawl upon entering, although previous studies (see for example, Main and Sangster, 1981; He et al., 2008) have observed flatfish swimming in the belly or codend areas. Taken together, these observations support the theory that flatfish may discontinue swimming in the trawl mouth (in part) as a behavioural decision rather than simply metabolic exhaustion (see further discussion by Winger et al., 2010).

Behaviour not only influences the residence time of an individual, it also influences the selectivity of the footgear. Fish length and end density were less influential than gait or behaviour on footgear selectivity. There were similarities in the footgear selectivity of large yellowtail and Greenland halibut (Albert et al., 2003), however their 20% estimate of small individual Greenland halibut escaping underneath the footgear was higher than in this study. This difference is not entirely unexpected as underwater experimental observations of rigging mini-sampling nets behind the footgear have repeatedly demonstrated that escapement under the trawl can be species-specific and size-dependent, depending on the bottom trawl used in their studies (Korotkov, 1970; Engås and Godø, 1989; DeAlteris et al., 1992; Walsh, 1992; Weinberg and Munro, 1999; Ingólfsson and Jørgensen, 2006). Though fish length had a no influence on selectivity in the current study, end behaviour was observed to have a significant effect on the final fate of yellowtail in the trawl mouth. Individual yellowtail that swam close to the seabed always escaped. Ryer (2008) discussed the significance of this anti-predator strategy and indicated that because of flatfish morphology and their tendency to spend a lot of time lying on the substrate, they can easily see predators coming from above or on the same plane. Therefore when flatfish stay swimming close to the seabed they are always keeping the threat (footgear) in view. Choosing to rise vertically moves the individual flatfish out of the immediate threat of the footgear while loosing sight of the footgear (predator) below (zone of influence; Ryer et al., 2010). Unfortunately, this anti-predatory strategy resulted in 100% of yellowtail being caught. On the other hand, yellowtail that swam across the trawl path had an almost 50:50 chance of actively escaping underneath the footgear or being caught. Beamish (1966) speculated that individuals facing the wings have a greater possibility of escaping. Only 2% of yellowtail collided with the trawl gear before escaping. However, should these escapes result in death, I speculate that a 2% (unaccounted) fishing mortality is low. I realise that using only individuals that collided with the footgear prior to escapement is a minimal estimate of fishing mortality and does not account for individuals that were hit by the footgear after escaping or overrun by the trawl in the capture zone (zone 3). Even with a minimal estimate of 2% (unaccounted) fishing mortality, I believe that with the high biomass and low quotas of the Grand Bank yellowtail stock, this mortality should not affect the sustainability of the fishery.

Walsh and Godø (2003) argued that any modelling of trawl induced fish behaviour has to consider length and end density as possible drivers of the capture process. Both of these variables were included in the analyses, however, neither were found to affect the fate of an individual's selectivity. I argue that behavioural selectivity at the footgear dominates the capture process. This study has shown that it is the flatfish's end behavioural response that decides the fate of the individual once they arrive at the mouth of the trawl.

Observing species-specific behaviour in underwater environments presents some unique technological challenges. The ability of traditional optical camera systems to detect individual fish in relation to trawl components (such as footgear, netting panels, floats, and doors) depends largely on their contrast with the background and are therefore dependent on the properties of the water, including the direction and intensity of the illumination and/or ambient light. Given that flatfish are often cryptically concealed against their habitat (i.e., background), many *in situ* behavioural studies have failed to detect the subtle differences in morphology necessary for discrimination between similar species of flatfish (Hemmings, 1973; Main and Sangster, 1981; Bublitz, 1996; Krag et al., 2009). The high definition (HD) self-contained camera system developed for this research permitted the identification of yellowtail with a high degree of certainty (72%). However, the absence of concentrations of American plaice in the study area due to areal bycatch restrictions, limited the initial objective of studying the trawl-induced behaviours of both flatfish species.

The use of the footgear reference length limited somewhat my ability to accurately measure the length of individuals and resulted in categorizing length into two broad categories, i.e., small and large. Consequently in those analyses where length was modelled as a covariate the observation sample size was reduced by 24% with the elimination of the unidentified length group. Albert et al. (2003) concluded that their inability to detect length dependent behaviour was due to lack of precision in estimating the reference length. Since many observations were lost due to the lack of precision in estimating the reference length in this study, I draw a similar conclusion. To overcome this limitation, future studies could experiment with stereophotography (Petrell et al., 1997; Harvey et al., 2002) or laser (Yanase et al., 2009) technologies to more accurately measure length.

Sample size can affect the probability of detecting statistically significant results and their interpretations (Type II error). For residence time, the use of 150 individuals showed no predictor variable being significant. However, when all assumptions were removed (i.e., through randomization), the model showed that only start trawl mouth behaviour was important in explaining variation in residence time. Fish length, gait, and substrate type were not significant in the model nor in the randomization. MLRs use the maximum likelihood method to estimate parameters (Agresti, 2007), and require a large sample size for performing model diagnostics, unlike some statistical models such as logistic regression. Although the full MLR model results gave a poor fit to the data (p = 0.81), with a sample size of 150 individuals the MLR software issued no warnings indicating fault with the analysis and I conclude that the results support the theory of orientation of yellowtail described above. A larger sample size for the GzLM, the selectivity analysis, may also have resulted in a length-dependent density-dependent selection. Nevertheless I am confident that the choice of statistical models was appropriate.

Behavioural studies investigating the interaction between fish and bottom trawls have increased in numbers over the past couple of decades in response to the need to develop technical devices to mitigate bycatch in commercial fisheries, and to understand the effect of fish behaviour on catchability in scientific resource surveys. This study provides valuable insight into the behaviour of yellowtail at the mouth of a bottom trawl, a species that has never before been identified with certainty from video footage, This is the first stage in developing the scientific approach for estimating and understanding the behavioural differences between yellowtail and plaice with the goal to exploit these differences in designing a species specific trawl to minimize plaice bycatch.

Table 3.1 Location, depth, detail of catch and number of observations of yellowtail made at each tow with video footage.

Tow	Latitude	Longitude	Depth (m)	Catch Size (Kg)	Percentage (%) of flatfish in catch			Observations (# of yellowtail)
					yellowtail flounder	American plaice	witch flounder	
1	4527.78	5152.28	82.3	2875	86	14		44
2	4526.27	5213.15	73.2	1725	92	8		38
3	4525.79	5152.27	80.5	2944	84	15	1	27
4	4523.58	5110.49	69.5	2530	92	8		46
5	4527.26	5117.00	69.5	2392	90	10		35

Table 3.2 Description of coding for each of the eight variables used in the post-collection footage analysis.

Code	Species	Length	Substrate Type	Gait *	Trawl Mouth Behaviour † (Coded twice, Start and End)	Trawl Interaction	Orientation
1	Yellowtail flounder	Small - *<30cm*	Shells - *sand with 10-20% shells*	Continuous Kicking	Swim Across - *swimming across the path of the trawl*	Actively Escape - *escape using gear*	facing the vessel
2	Unidentified	Unidentified	Sand - *more than 95% sand*	Cruise and Kick	Horizontal Rise - *swimming facing the vessel, parallel to the seabed while moving upwards*	Overtaken and Escape - *overtaken by gear*	45° starboard side of vessel
3		Large - *>30cm*	Sand Dollars - *sand with 10-20% sand dollars*	Continuous Cruising	Swim near Seabed - *swimming close to the seabed facing the vessel or zigzagging*	Overtaken and Caught - *overtaken by trawl while facing the vessel*	facing starboard
4					Swim below footgear - *swimming between the height of the footgear and the seabed*	Actively Caught - *swim into trawl*	45° starboard side of trawl
5					Swim above footgear - *swimming above the height of the footgear*	Collide and Caught - *collide with the gear and enter the trawl*	facing the trawl
6					Vertical Rise - *swimming facing up, perpendicular to the seabed while moving upwards*	Collide and Escape - *collide with the gear and escape*	45° port side of trawl
7							facing port
8							45° port side of vessel

* Gait employed by the fish (Webb, 1994; Peake and Farrell, 2004; Winger et al., 2004).

† Trawl mouth behaviours based on the descriptions in Albert et al. (2003).

Table 3.3 Summary of Rayleigh Test for the orientation of yellowtail flounder on or in the substrate in relation to a) location and b) start trawl mouth behaviour. In all but one test (vertical rise), the orientation was found to be non-random.

Category		N	z value	Pr(>z)
a) Location	Port	46	18.54	<0.001
	Middle	97	46.98	<0.001
	Starboard	47	22.87	<0.001
b) Start Behaviour	Swim across	110	52.44	<0.001
	Horizontal rise	11	5.93	0.001
	Swim near seabed	60	29.78	<0.001
	Vertical rise	09	1.99	0.137

Table 3.4 Summary of statistical models for three of the hypotheses. a) Model 1 using MLR: Start Behaviour ~ Length + Start Density + Substrate Type, b) Model 2 using GLM; Residence Time ~ Length + Start Density + Substrate Type + Gait + Start Behaviour, c) Rand.2 is a randomization of Model 1 replicated 5000 times, d) Model 3 using GzLM: Fate of an individual ~ Length + End Density + Substrate Type + Gait + End Behaviour, e) Rand.3 is a randomization of Model 3 replicated 5000 times, All models and randomizations are with a reduced sample size of 150 observations (excluding the unidentified length category). All observations are individual, unique flatfish.

	a) Model 1		b) Model 2		c) Rand.2	d) Model 3		e) Rand.3
Factor	$x^2_{(df, N)}$	Pr (>x)	F $_{(df, res.df)}$	Pr (>F)	Pr (>F)	$x^2_{(df, N)}$	Pr (>x)	Pr (>x)
Model	$7.64_{(12, N = 150)}$	0.81	$1.66_{(9, 140)}$	0.100				
Length	$3.19_{(3, N = 150)}$	0.36	$0.01_{(1, 140)}$	0.914	1.000	$3.66_{(1, N = 150)}$	0.056	0.067
Start Density	$3.89_{(3, N = 150)}$	0.27	$0.86_{(1, 140)}$	0.356	0.611			
End Density						$2.56_{(1, N = 150)}$	0.109	0.118
Substrate Type	$0.86_{(6, N = 150)}$	0.99	$1.24_{(2, 140)}$	0.292	0.126	$3.84_{(2, N = 150)}$	0.146	0.152
Gait			$1.28_{(2, 140)}$	0.281	0.317	$8.31_{(2, N = 150)}$	0.016	0.023
Start Behaviour			$1.38_{(3, 140)}$	0.250	0.046			
End Behaviour						$115.50_{(3, N=150)}$	<0.001	<0.001

Table 3.5 Summary of residence time for yellowtail flounder and per sub-category. N is the sample size; mean residence time, standard error (SE), 95% confidence intervals (CI) and range are in seconds (s). The mean density at the start of the observation, 95% Confidence Intervals (CI) and range are number of flatfish.

Category		N	Mean (SE)	95% CI	Range
Species	yellowtail flounder	150	3.9 (0.30)	0.59	0.8 – 31.9
Length	large	94	4.0 (0.44)	0.87	0.8 – 31.9
	Small	56	3.7 (0.32)	0.64	1.2 – 13.7
Substrate Type	10-20% shells	58	3.6 (0.31)	0.61	0.8 – 13.7
	Sand	46	3.4 (0.26)	0.52	0.9 – 7.4
	10-20% dollars	46	4.7 (0.85)	1.72	1.2 – 31.9
Gait	continuous kick	68	3.1 (0.29)	0.57	0.8 – 13.7
	Continuous cruise	5	3.2 (0.52)	1.45	2.0 – 4.5
	Kick and cruise	77	4.6 (0.51)	1.02	0.8 – 31.9
Start Behaviour	Swim across	88	3.8 (0.29)	0.58	1.2 – 22.9
	Horizontal rise	6	3.6 (0.56)	1.45	1.6 – 4.9
	Swim near seabed	47	4.6 (0.76)	1.53	0.9 – 31.9
	Vertical rise	09	1.1 (0.09)	0.21	0.8 – 1.6
Start Density		150	13.0 (0.48)	0.95	2.0 – 30.0

Table 3.6 Summary of the fate of an individual for yellowtail flounder and per category. N is the sample size; Escaped, Caught and the main trawl interaction (TI) in parenthesis are in percentage. Trawl interactions are A – actively escape/caught, O – over taken by the trawl or C – collided with the gear. The overall, escaped and caught end densities are calculated. The mean density at the end of the observation, 95% Confidence Intervals (CI) and range are number of flatfish.

Category		N	Escaped (TI)	Caught (TI)	
Species	yellowtail flounder	150	37 (C 2)		
Length	large	94	35		
	Small	56	39		
Substrate	10-20% shells	58	40		
Type	Sand	46	41		
	10-20% dollars	46	28		
Gait	continuous kick	68	38		
	Continuous cruise	5	60		
	Kick and cruise	77	34		
End	Swim across	63	54 (A 49)	46 (A 43)	
Behaviour	Horizontal rise	34	3	97 (O 47, A 50)	
	Swim near seabed	20	100 (O 55)	0	
	Vertical rise	33	0	100 (A 79)	
					Overall
End	Mean (SE)		15.4 (1.00)	14.5 (0.59)	14.8(0.52)
Density	95% CI		2.00	1.1	1.03
	Range		4 – 41	2 – 30	2 – 41

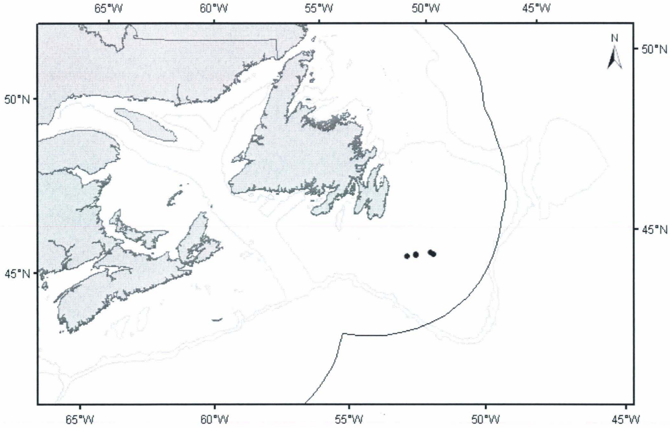

Figure 3.1 Map of the study site. Tows were conducted on the southern part of the Grand Bank off eastern Newfoundland. The black circles indicate the location of each tow. The solid line is the exclusive economic zone (EEZ).

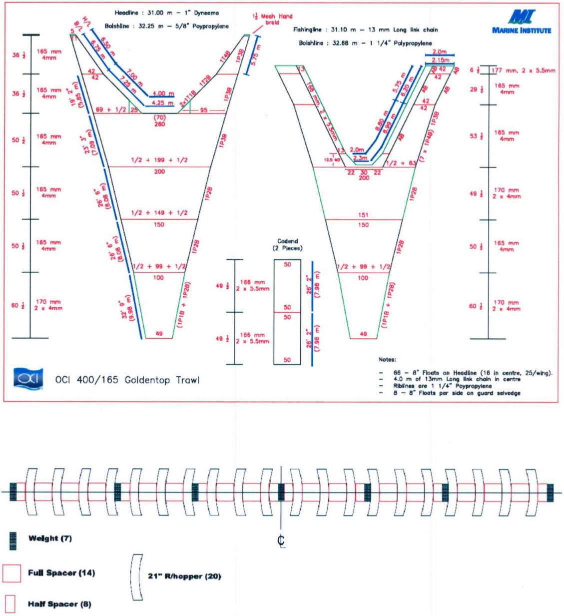

Figure 3.2 Schematic trawl plan and bosom footgear for the Goldentop trawl used by OCI vessel F/V Aqviq (Winger et al., 2010b).

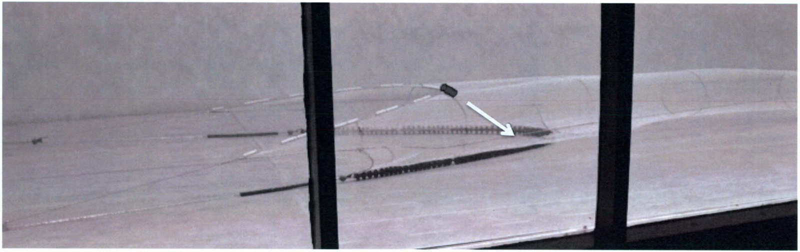

Figure 3.3 Self-contained underwater camera placement on the bottom trawl. The camera was placed in the middle of the headline positioned forward of the footgear with the mouth of the trawl in the field of view.

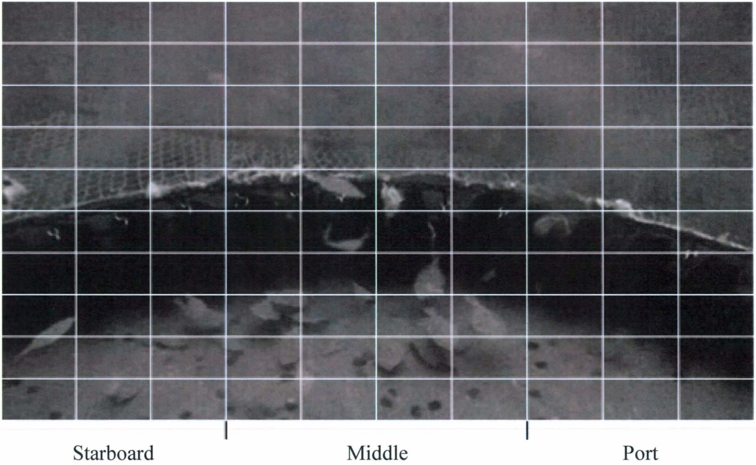

Figure 3.4 Example of grid for the post-collection footage. The middle 4 squares represent the centre of the footgear and the 3 squares on either side are the port and starboard.

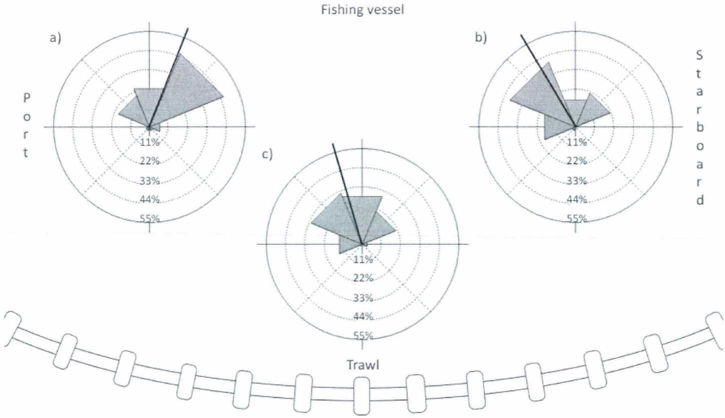

Figure 3.5 Percentage of initial orientation of yellowtail flounder on or in the substrate in relation to the centre of the footgear. Individuals were either categorized as on the a) port, b) starboard side or in the c) middle of the trawl. The black lines indicate the mean direction. A total of 46 observations on the port, 47 on the starboard and 97 in the middle were used.

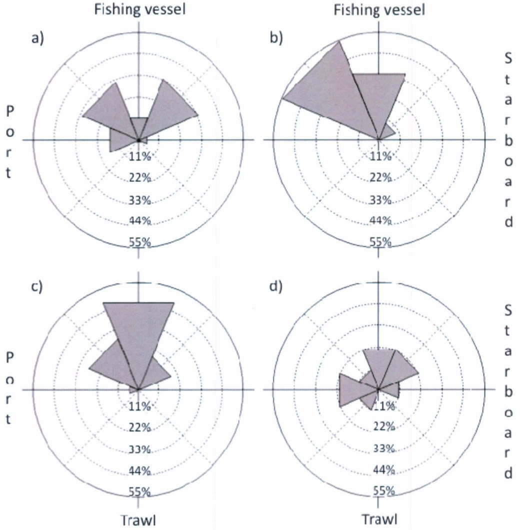

Figure 3.6 Percentage of initial orientation of yellowtail flounder on or in the substrate for each of the four start behaviours; a) swim across the trawl path (N = 75), b) horizontal rise (N = 51), c) swim near the seabed (N = 20) and d) vertical rise (N = 44).

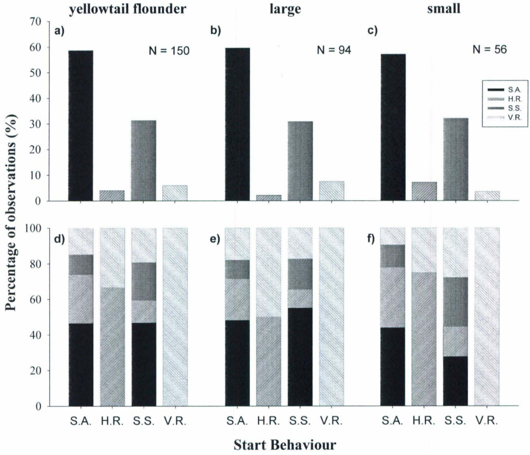

Figure 3.7 Sequence of trawl mouth behaviours for yellowtail flounder, large and small individuals. Percentage of start behaviours (a-c) and the percentage of behavioural changes (d-f) for each of the start behaviours. Behaviours are; S.A. – swim across, H.R. – horizontal rise, S.S. – swim near seabed, V.R. – vertical rise.

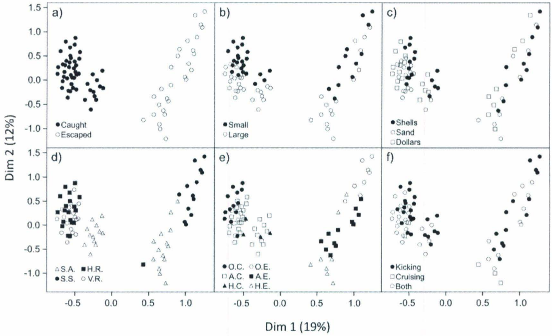

Figure 3.8 Graphical representation of the multiple correspondence analysis (explaining 31% of the data) of all categorical variables; a) fate of an individual, b) length, c) substrate type, d) end behaviour, e) trawl interactions, and f) gait. End behaviours are; S.A. – swim across, H.R. – horizontal rise, S.S. – swim near seabed, V.R. – vertical rise. Trawl interactions are; O.C. – overtaken and caught, A.C. – actively caught, C.C. – collide and caught, O.E. – overtaken and escape, A.E. – actively escape, C.E. – collide and escape. The x-axis of each panel (Dimension 1) represents final fate of an individual. Individual fish with a value less than zero escaped under the footgear, while those greater than zero were captured. The y-axis represents 12% of the variation in the data.

Chapter 4. Summary

The object of this study was to develop a camera system capable of identifying flatfish species and to use the system to observe the behaviour of yellowtail flounder (*Limanda ferruginea*; here after named yellowtail) in the mouth of a commercial demersal trawl. The development of a high definition (HD) self-contained underwater camera system (chapter 2) illustrated that in a laboratory setting, HD camera systems have a significant improvement over traditional standard definition camera systems and can identify the finer details needed to differentiate between morphologically similar species (i.e. flatfish). Laboratory experiments also found that updating the recording device could also improve the image quality but not to the same level as HD. Field trials further supported the results observed in the laboratory, allowing yellowtail to be identified with high certainty via video footage from the HD camera system. Also, the HD camera when attached to a demersal trawl performed well in low light environments without the need of artificial lights. It is hoped that the findings of chapter 2 will help guide other researchers considering the upgrade of their camera systems as to whether HD is worth the upgrade or whether just upgrading the recording device is sufficient.

In chapter 3, the behaviour of yellowtail in the mouth of the trawl was observed, quantified and a series of novel statistical tests were applied to evaluate hypotheses related to a) orientation on or in the substrate, b) trawl mouth behaviour, c) residence time, and d) footgear selectivity. The results suggested that the orientation of individuals on or in the substrate was evidence of previous herding and influenced the initial behaviour response of yellowtail to the footgear (and as a result flatfish). Unlike roundfish, which are morphologically built to move quickly in the lateral plane, flatfish are unable to change swimming direction in the lateral plane quickly. This limits their choice of swimming behaviours after rising out of the seafloor to either a) the direction they are orientated or b) to rise vertically and to be overtaken by the trawl. Once the individual was displaying its initial swimming behaviour, individuals would most likely reassess the situation and change its trawl mouth behaviour was observed (except for individuals that rose vertically). Multiple factors influenced the fate of the individual (whether the individual was caught or escaped), including its choice of end behaviour. In Chapter 3, I also stressed the importance of behaviour-dependent selectivity, together with other common variables such as length and density.

Underwater cameras are a demonstrated method for *in situ* observations of fish behaviour, nevertheless, using cameras in the field can have some hurdles. I had hoped to collect footage from four trips out on the Grand Bank, each trip ranging from 16 – 21 days, however, two of the trips resulted in no viable footage due to firstly, unexpected weather and secondly, camera problems. Firstly, a hurricane came through before one of the trips that a) stirred up the sediment and b) increased the seafloor temperatures of up to 10 degrees (personal observations). The decreased visibility meant that less natural light was reaching the camera system and the footage was too dark to use. I did not want to use artificial white lights as it is unclear as to if white lights affect fish behaviour. Infrared and red lights were used instead but with limited success at that time. Secondly, on separate trips, the camera system hit the vessel ramp and deck during haul-back, resulting in damage to critical circuitry that prevented the use of the camera system for significant time periods of the cruise. Both the weather and camera issues resulted in viable footage for chapter 2 and 3 being collected on two of the four trips.

Originally, the objective of this study was to identify behavioural differences between two flatfish species in the hopes of modifying the gear to become more species selective. It was anticipated that American plaice (*Hippoglossoides platessoides*; here after named plaice) would be visible in the footage and that differences between yellowtail and plaice could be quantified. Unfortunately, plaice were unable to be identified with high certainty in the available footage. It is speculated, that the low number of plaice in the catch (8 – 15 % of catch weight) decreased the probability of a) identifying individuals with certainty and b) observing them rise off the substrate in the field of view. Plaice are a larger fish and therefore the percentage of catch weight would result in a lower percentage of catch numbers. For these reasons, plaice were unable to be identified via underwater footage in this study. However, I believe that plaice would be identified with high certainty in areas with greater concentrations of plaice,

Although, plaice were unable to be quantified, this study will represent the first published statistical analysis of trawl induced fish behaviour and has benefited the industry. The quantified data collected in the study has lead to gear testing to reduce the escapement rate for yellowtail flounder. It is also the first stage in developing a scientific approach for estimating and understanding the behavioural differences between yellowtail flounder and American plaice with the goal to exploit these differences in designing a species specific trawl to minimize plaice bycatch and smaller, less valuable yellowtail.

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