Modelling the White Shark's Ability to Premeditate the Actions of Cape Fur Seals

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Declaration
This dissertation is submitted to the University of Bath in accordance with the requirements of the degree of Bachelor of Science in the Department of Computer Science. No portion of the work in this dissertation has been submitted in support of an application for any other degree or qualification of this or any other university or institution of learning. Except where specifically acknowledged, it is the work of the author.

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Abstract

White sharks are one of the most feared predators of the sea. Understanding their hunting strategies and predatory techniques is no small task due to their large range of sensory abilities and optimisation methods. This dissertation explores the idea that white sharks can premeditate their attacks on pinnipeds using memory rather than sensory information alone. This is done using an Agent Based Model (ABM) to contrast intelligent shark agents with memory capabilities to those without and then comparing these findings to real world data [R A Martin et al, 2005]. It is shown that there is positive correlation between the intelligent shark agents and the real world data in comparison to the basic shark agents. It is concluded that there is some substantial evidence to support the theory of white sharks premeditating attacks on Cape fur seals and future extensions of the work is suggested. An increase in global knowledge of white shark behaviour increases white shark awareness and preservation techniques for one of the greatest predators in existence.

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1. Introduction

The white shark (*Carcharodon carcharias*) has been an inhabitant of the planet for 65 million years [Natural History Museum, 2008] and is part of the shark family which has existed for 450 million years [Natural History Museum, 2008] and it is one of the very few remaining species in that family. Therefore it can be deduced as one of the greatest survivalist species in the shark family and possibly one of the greatest in existence. Yet research has shown that there has been a decline in the white shark population of between 60-95% in the last 50 years [D Reid et al, 1992] and in 2008 it is listed by the ICNU as 'threatened' [IUCN Red list, 2008].This is due to over fishing, trophy hunting, environment deterioration and other human factors. Certain human measures have been taken to protect and preserve white sharks from our own methods of destruction but little is known about the white shark's own preservation techniques. The white shark's ability to survive into modern times from the prehistoric ages alone is testament to its intelligence and ability to successfully target, track and consume prey without expending more than the necessary amount of energy to do so.

With the white shark's huge dietary variety of mammals, pinnipeds, fish, crustaceans, rays and some birds it is easy to mistake the shark for an opportunistic feeder or one with little preference to prey type. It is true that the white shark has the ability to hunt and consume near enough anything in its waters, owed largely to its 1.8 tonne bite [S Wroe et al, 2008] but the white shark does so with great intelligence and tact to maximise its strike success and minimise energy expenditure. Although renowned for its bite ferocity, agility and short-burst speed one of the underestimated hunting strategies of the white shark is its intelligence. It has been observed [R A Martin et al, 2005] that a white shark can intercept a Cape fur seal's movements before it has made them and even position itself in the exact spot of a seal's landing before it has jumped out the water and this has even been captured on video. This ability could be the white shark's greatest asset when fighting for survival against quicker, more agile prey such as seals and pinnipeds, and one of its most underestimated and unknown.

An ABM simulation is proposed to model the hunting tactics and techniques of the white shark on Cape fur seals to try and determine if it is possible for a white shark to premeditate the movements of a seal, and if so to what extent it can do so. It will also provide an insight into the predatory techniques of the white shark and the evasive and defensive techniques of the Cape fur seal. This model will allow a visualisation of the white shark's hunting strategy and the Cape fur seal's behavior including flocking and grouping techniques employed to avoid predation.

The model will provide the ability to observe what is often difficult to observe as a third party in reality due to safety issues and the scope and distance of the environment. More importantly the simulation will allow comparison between intelligent shark agents, unintelligent shark agents and the real life observations recorded by Martin to find if there is any relationship between the three. It will also remove any physical third party presence, which has been shown to affect the white shark's behaviour and interaction with Cape fur seals [R Karl Laroche, 2006] and will therefore provide a unique birds-eye observation perspective on the ecosystem.

By improving understanding of white sharks hunting techniques and predatory tactics the understanding of the feeding and survival of the white shark will improve. This should help to aid the human effort for white shark captivity and preservation which has had mixed success thus far [Monterey Bay Aquarium, 2008]. By determining exactly how a shark indentifies prey and routinely predates, particularly if it creates neurological map of its ecosystem, will give a clearer indication on why feeding has proven difficult for white sharks in captivity. It will also undermine the importance of the small ecosystems such as Seal Island that are repeatedly visited by white sharks every year and remain a staple of support for white shark survival.

2. Aims and Objectives

2.1 Aim

To improve understanding of white shark hunting techniques and predatory techniques with the aim of understanding specifically if the shark can successfully premeditate the movements and actions of Cape fur seals when hunting.

2.2 Objectives

- Comprehensively understand the behavioural patterns and predatory strategies of the white shark through research papers and other means of secondary research.
- Create hypotheses of how the white shark may be able to premeditate prey movements using secondary research as a basis.
- Use these hypotheses as a basis for the design and implementation of an ABM to be proven or disproven.
- Create an ABM that accurately represents the behavior of white sharks and Cape fur seals to the extent of the relevance to the investigation into white shark premeditation.
- Create experiments from the finished model that will provide data from which information can be derived regarding the behaviour and actions of the predator and prey which can lead to conclusions of these results regarding if and how premeditation of prey movement occurs by the white shark.
- Improve knowledge of white shark behaviour from the information derived from the results generated from the ABM simulation.
- Provide ideas for future research if relevant from the conclusions.

3. Premeditation

Premeditation is the planning of an event or attack reliant of an anticipation of an event before the event occurs in real time, without necessarily consciously acknowledging the prediction before the event. So the premeditation of events leading up to the successful capture of prey would depend on the individual cognitive skills and neural development of the individual shark, possibly increasing as the age of the shark increases. The development of cognitive skills, particularly spatial learning and problem solving "seems to be associated with visual orientation and well-structured habitats in fish" [K Kortschal et al, 1998] and as white sharks have "excellent photopic (bright-light) colour vision" [Shark Research Committee, 2008] its therefore perceivable that white sharks excel in cognitive skills relative to other species in the fish family.

3.1 Definition

To truly understand the concepts of premeditation during predation you must fragment the idea into categories:

(1) The prediction of spatial areas and time periods where predation is highly likely or most likely to occur within an ecosystem
(2) The evaluation of spatial areas that are less likely to produce successful predation and the analysis of hunting patterns compared to (1)
(3) The prediction of specific animal flocking *behaviour to increase the chance of successful predation

*Behaviour is defined as the physical movements of the animal and patterns of entering and leaving the area of possible predation. Also includes its defensive flocking techniques such as grouping and evasive swimming.

An obvious place to expand this definition is the analysis of the first and second categories. Analysing the spatial areas that are recognised and frequented by the white shark due to success rates of predation over unsuccessful areas where predation has occurred less frequently is an interpretation of these categories. The ecosystem that the study will be based on is that of Seal Island [R A Martin et al, 2005], the case study in question will be used as a means of raw data for the simulation to define characteristics of the white shark agent and the Cape fur seal agent. This case study is concerned with the patterns of movements of animats across the spatial domain of the island without time constraints.

The white shark is as diverse in diet as it is in breeding as they have been known to make oceanic migrations [B D Bruce et al, 2003], which suggests long term memory and environmental association with hunting and breeding on a global scale. This is again suggestive of the enormous capacity for spatial awareness and cognitive memory of the white shark.

There is no doubt from recent research that the spatial awareness of white sharks is transoceanic and the frequency of transoceanic return journeys of both male and female white sharks is far higher than estimated previously [R Bonfil et al, 2005]. Philopatry in white sharks is confirmed in the study and this shows how white sharks are spatially aware on a global scale to better chances of breeding and predation. The simulation proposed will concentrate on a small area or single ecosystem, to investigate how precise the spatial awareness of the white shark extends and its association with successful predation. A theory to the successful navigation of such large transoceanic journeys is down to visual stimuli and celestial cues, much like that of a human, rather than the previously speculated magnetic gradients of the Earth's magnetic field [R Bonfil et al, 2005]. This would be an applicable theory to explain the navigation and spatial recognition on a smaller scale ecosystem such as Seal Island [R A Martin et al, 2005] and how the shark would be able to distinguish and recognise certain areas, whether these areas are associated with successful predation or not is still somewhat unexplored.

One of the most interesting examples of premeditative attack in white shark predation is described when an observation of a female white shark predicting the defensive manoeuvre of a Cape fur seal as it leapt from the water vertically as a means of reorientation, to fall into the waiting jaws of the shark. This instance is an example of the third category of premeditation where the shark is familiar with the evasive movements of the prey, recognises from memory the movements (or sequence of movements) and premeditates an attack based on a prediction of an occurring movement. This is a theory based on the sharks learning ability of a recognised prey.

3.2 White Shark Cognition

Fish are largely considered primitive animals and intellectually inferior to aquatic mammals that share their environment. Avoidance learning [J Topál et al, 1999] in small defensive fish has proven that fish can recognise, learn and avoid the shapes of their predators and spatial areas associated with predators once exposed to certain stimuli [A Miklósi et al, 1989] that evoke strong instincts such as fear through memory and association with the particular stimuli (previous predator encounters, electric shock treatment etc). The instinct to explore is provoked by unfamiliar stimuli in unfamiliar surroundings and can be overridden when a familiar stimulus is encountered from the long-term memory and the associated instinct is evoked. The recognition of a long-term memory of a new object may develop in a matter of minutes [V Csányi et al, 1989] contrary to the myth that many fish [C Brown et al, 2006] have extreme short term memory only.

Such studies are easily carried out on small species such as the paradise fish (Macropodus opercularis) [J Topál et al, 1999] and other small prey whereas to develop and carry out a study on a dominant predator such as the white shark holds more complications. The issues with maintaining captured white sharks are well documented [Monterey Bay Aquarium, 2008] but many of the characteristics of the spatial awareness of the smaller fish could be applicable to larger predators and would go to explain some premeditative attacks. If an area became associated with certain stimuli (successful predation or breeding) then strong instincts could be defined with those spatial areas when the stimuli are recognised by the white sharks long term memory or even when the stimulus is removed the instinct is retained in that area. This would explain how the shark can do transoceanic journeys and still be able to return to its exact birthing place to breed and how it can recognise and remain in a sector of an ecosystem that will produce the highest chance of predation statistically.

The ability to premeditate a successful attack is therefore defined as the ability to locate and recognise areas where the attack may take place before it does. This is obviously done through the recognition of the correct spatial areas through certain stimuli that the shark has learnt from. It is the ability to learn that makes the premeditative attack a possibility, which in turn give the ability to recognise spatial areas but equally as important, the ability to recognise prey.

The white shark is famed for the misrecognition of its prey, often blaming its inability to distinguish a swimmer or surfboard from other surface prey has been mistakenly used as a theory for shark attack. This statement alone suggests that the outline, shape or physical appearance is a key factor for prey recognition within white sharks opposed to any other sensory recognition. On the contrary, the shark uses multisensory techniques to determine potential prey. Excellent vision has already been defined as part of the white sharks arsenal; shark attacks on humans are usually down to curiosity and lack of experience. As shark attacks are rare white sharks have little or no experience when predating humans, which is why exploratory bites are often taken to determine the palatability of the prey [E Ritter et al, 2004]. This shows that the white shark's ability to learn is through trial and error and not only recognition through visual means but recognition through chemoreception.

Assumption of the recognition of prey is needed when discussing a case such as Seal Island where white sharks and seals pursue a battle for food and survival for a period of 2 to 4 months of the year when the water temperature is highest. Considering this the most important factors for a successful premeditative attack would be the spatial positioning of the shark, including boundaries of depth, and also the time of the attack [R K Laroche et al, 2008]. The time of the attack is a simple basis of how well the shark can utilise its visual advantage to recognise and hunt the pinnipeds which is when there is most sunlight [R A Martin et al, 2005]. The percentage of sharks in the water lowers reaching dusk and is very few during night, at dawn the percentage of sharks (and consequently attacks) increases greatly as there is a high population of seals in the water and the visibility is improving.

Given the factors presented describing the definition of a premeditative shark attack and given the evidence to describe how a shark may go about premeditating the attack, it is important to analyse further the processes and sequences of the specific shark and seal behaviour leading up to an attack. Now it is understood how the shark has the ability to learn about when and where best to attack, to understand how the shark attacks will help understand to what extent of the attack is premeditated by the shark and how much is down to factors such as predatory experience, predatory techniques, evasive techniques, constant factors of the individual (speed, strength, awareness etc) and how much is down to luck. This will give us a better understanding if the (3) categorisation of the premeditative theory is possible.

4. Shark Predation and Seal Evasion

The key to understanding the white shark's ability to premeditate its attacks is to fully understand the way it hunts. It is one thing to understand how a white shark can learn its environments and spatial areas from experience but to understand if a white shark can learn its prey, how it behaves and how it reacts to predation is far more complicated. By looking at how sharks can distinguish between preys and how it adapts predation strategies through this should give a better insight into what the shark understands about its prey.

The array of prey that the white shark has been known to feed on ranges from fish, birds, land mammals, cetaceans, pinnipeds, chelonians [I K Fergusson et al, 2000] and even inanimate objects such as buoys and boats [R S Collier et al, 1996]. The notoriously versatile diet of the white shark is attributed to its curiosity instinct [J Topál et al, 1999] and it has been another huge disadvantage to the successful human captivity of white sharks [Monterey Bay Aquarium, 2008] as there are very few species it can coexist with. This could be due to its position as head of the food chain with no natural predators, and with its vast distances of travel the white shark needs to feed often to sustain its energy expenditure.

The curiosity instinct in the white shark could be more prevalent than in fish with natural predators as the fear instinct is overriding when the fish senses danger and true to Darwin's theory of natural selection a fish that is often predated will adapt defensive techniques. Subsequently its exploratory instinct is suppressed and its feeding instincts are relative to one or a few known species. Similarly a fish who often hunts will adapt better hunting techniques but retain an exploratory instinct, so if an object is identified as possible prey but not entirely recognised by the white shark it exhibits behaviour that is both exploratory and also aggressive. Subsequently the white sharks are defenseless on the rare occasion they are attacked or predated [Marine Mammal Science, 1999]. This would explain the palatability bites described by Ritter.

4.1 Decision Tree

This mixture of exploration and aggression in its predation techniques is shown by a sequence of actions that depict the shark detecting a possible prey, stalking and analysing the prey, testing the prey and consequently deciding to launch an attack. Alternatively if the shark recognises the prey they may launch an attack from there, or disregard the object completely. Here is a decision tree to represent the process;

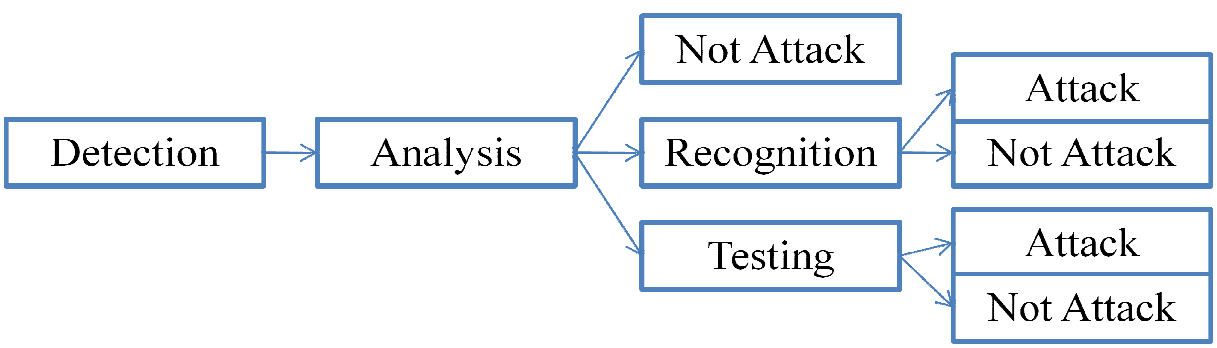


Fig 1 Shark Predation Decision Tree

The detection process often starts when the shape, outline or movements of a prey attract the white sharks attention. White sharks are known to swim predominantly at the bottom of the seabed [A P Klimley at al, 1996] and are attracted by outlines on the surface which is why 13.9% [R A Martin et al, 2005] of shark attacks on Cape fur seals are upward strikes from below the prey, the second most common strike after attacking an previously injured seal laterally. This is another example of sharks benefiting from sunlight and daytime hunting.

The analysis or stalking phase is the most interesting, and in some cases can last for days. A small fishing vessel was stalked for two days before being tested by the same white shark [The Shark Research Committee, 2008]. Analysis can often included stalking from the bottom of the seabed where the shark remains undetected or it can be from the surface [The Shark Research Committee, 2008]. Analysis also includes visual analysis and sensory analysis of the movement of the object [E Ritter et al, 2004]. White sharks like many fish can detect change in water pressure from very close range using the lateral line [J Mogdans et al, 2001]. The lateral line is a receptor system on the surface of the white shark that can detect hydrodynamic changes in water pressure which is why white sharks are seen to swim very closely to an object with its snout without biting, or even bumping the object. Such changes can determine the identification of the object under scrutiny [J Engelmann et al, 2001]. This could also be seen as a means of testing an object's validity as prey. It has been proven that the more movement a surface object makes the more likely the shark is to bite or test the object [E Ritter et al, 2004].

The circling of the object is a means for the shark to take a visual analysis of the object and also to stay orientated in regards to the prey before testing or attacking the object. The eye roll [E Ritter et al, 2004] ability of the white shark means the shark can analyse an object visually while its movements can remain on a circular course, the sunken position of the eyes on either side of the head also allow for good visual analysis from a perpendicular position relative to the object being assessed.

The testing phase as described previously by the palatability bite is also an assessment of the objects worth for consumption. Klimley's investigation into the consumption of different forms of bait by white sharks found that bait with a high blubber content (e.g. seals, pigs etc) were consistently accepted after a test bite compared to those with a low blubber content (e.g. sheep) which were consistently rejected after a test bite.

It is clear how the white shark uses multi sensory techniques to come to a decision as to whether to attack and consume an object including visual, skin sensors to detect hydrodynamic changes and body movement of the prey, taste and smell sensors to assess the palatability and possibly the worthiness of an objects consumption in regards to the energy expended and the energy gains from its consumption. From this information it is obvious that the white shark can tell a lot about its prey and that the stalking and assessment parts of the decision tree are definitely akin to the premeditation to attack. Trying and understand further the techniques used when attacking with intent to consume specific recognised prey will help to understand if the white shark can predict the evasive actions of the recognised prey and premeditate an attack.

4.2 Predating Pinnipeds

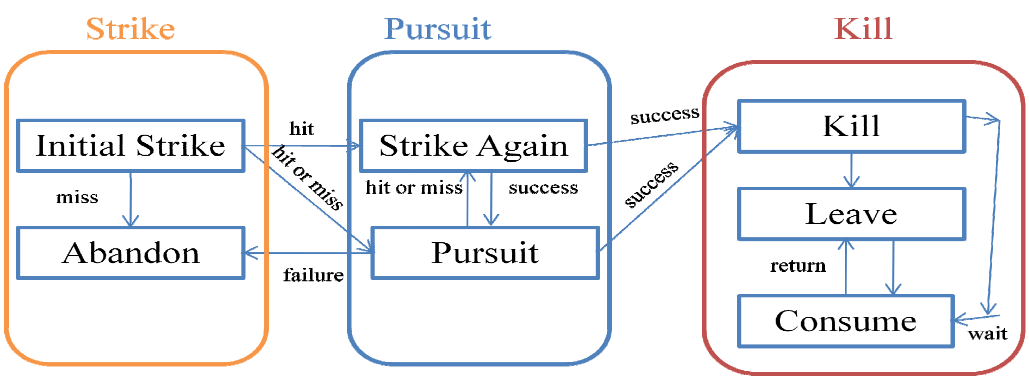
As this study focuses on Cape fur seals and the findings from R A Martin's [2005] study at Seal Island, I will be looking at the specifics of the predatory and evasive tactics of the white shark primarily on Cape fur seals but also pinnipeds in general.

Pinnipeds are marine mammals that live on land and sea. Their high fat content makes them the perfect prey for a predator needing maximum energy reward from a prey. Pinnipeds such as walrus are generally found in waters too cold for the white shark to venture, so pinnipeds such as seals and sea lions that venture into warmer waters particularly around California, Australia and South Africa tend to be the main provision of food for the white shark. The warmer temperature means that the pinnipeds have less fat content and are smaller in mass but still provide much needed energy through the high blubber content in comparison to other prey. Seals are particularly favoured over sea lions due to the higher success rate of predation when attacking seals [D G. Ainley et al, 1985].

Much of the white sharks attack strategy is based around the element of surprise, its attack from below and behind the prey is designed to immobilise the prey with the first strike to prevent fleeing. In many senses this strategy is based around premeditation as the strike is planned although there is also a high risk as an unsuccessful first strike will certainly lead to prey fleeing and can often mean an unsuccessful predation, particularly if the fleeing of the animal lasts greater than 2 minutes as the sharks stamina at high speeds is poor and means greater energy expenditure than the reward [R A Martin et al, 2005]. Therefore the attack is likely to be abandoned. The white shark attack strategy is said to be ideally suited for predation on pinnipeds [A P Klimley et al, 2001b] and although the variety of the white shark diet is large and a large majority of the white shark's food is scavenged from other white shark kills [A P Klimley et al, 2001] pinnipeds are the primary prey for white sharks.

Martin presents the idea of a shark attack on a pinniped in 5 phases of decision making with 4 phases of attack pattern with 20 recorded moves of attack from various phases of the attack pattern. The ideas presented are similar to those presented in the decision tree in the 5 phases of decision making "detection, identification, approach, subjugation, and consumption". The 4 phase attack procedure is; initial strike, secondary pursuit, prey capture and consumption. The initial strike is described as a vertical or 45 degree angle upward strike from below and behind the seal. After this, if unsuccessful in wounding or killing the seal the shark will follow the seal as it flees pursuing parallel to the seal and then attack with a lateral snap to effectively wound the seal from a perpendicular head position (to apply the highest amount of damage to the seal) although the body is still oriented parallel with the seal's route of escape. Alternatively the white shark may try another surface breach if the first is unsuccessful and if the prey is not fleeing (injured or in shock). From Martin's 4 phase attack procedure a proposed 3 phase action process has been derived as follows;

Fig 2 The Three Phase Action Process



The means of killing and consuming a single pinniped is not trivial; there are several variables to consider. The typical strategies of avoidance are fleeing, grouping, vigilance experience and occasionally mobbing. All predation of pinnipeds occurs in the previously defined danger zone as pinnipeds enter and leave, but not all evasive and defensive techniques are employed there.

4.3 Fleeing and Flocking

Fleeing is the primary flocking technique when a single pinniped is alerted of the white shark's intention to predate it. Flocking is the action of individuals fleeing as part of a group. Flocking often provides a high success rate of predation avoidance over fleeing. Pinnipeds are typically streamlined, agile and very competent swimmers and often have the edge in terms of speed on a white shark. Typically pinnipeds when fleeing will swim in a zigzag motion with varying depths, but always at a depth that is relatively close to the surface [R A Martin et al, 2005]. Pinnipeds also frequently leap between the air and water surface when fleeing and also leap vertically out of the water as a means of reorientation with land and associated safety. These methods are designed for confusion and are far more successful in flocks then during fleeing. It is the individual's ability to outlast the white shark for any significant amount of time during fleeing that will be the deciding factor in the successful evasion, which is co-dependent on the success of the initial strike phase of the attack procedure and the individual's ability to overcome shock.

4.4 Grouping and Vigilance

Groups provide a means of safety and a higher rate of successful predation avoidance for many species of prey, often providing confusion during flocking. In Martin's study at Seal Island, groups consisted of between one and fifteen with the larger groups having a significantly greater rate of escape or survival than the solitary groups which were more frequently targeted by the sharks. Vigilance is a key aspect to the successful detection of predators and is a common survival techniques employed by pinnipeds [J Fortuna, 2000]. Group vigilance is seen to improve with the larger group size which invariably means that the larger the group the more likely they are to detect a white shark and the ability to detect a shark has increased distance with an increased group size. The only existing piece of evidence that a white shark can predict the movement of a pinniped and premeditate an attack is while the Cape fur seal is performing a vigilance check to reorient itself with the safety of the shore [R A Martin et al, 2005]. This shows how important vigilance is to pinnipeds and how important the anticipation of a predator is in the successful evasion of one.

The white sharks choice of individual prey when attacking a group will be relative to the weakest, smallest and youngest as these factors are inversely proportional to the ability of evading predation. The choice of prey in the analysis stage of the decision tree will consider these factors and white sharks are often seen to go for juvenile or adult female pinnipeds for these reasons [P D Shaughnessy et al, 2007 and D G Ainley et al, 1985]. The choice of individual prey may change from the initial choice during the first strike as when a group is flocking the weakest individual is often alienated, alternatively the group flocking effect will confuse the shark from its initial choice and prevent predation, this is why single targets are preferred [R A Martin et al, 2005].

4.5 Experience

The experience of the predator and of the prey has a huge impact on the outcome of the predation event. Juvenile pups are often targeted [A P Klimley et al, 2001b] by white sharks and due to their lack of experience in evasion are often successfully consumed [R A Martin et al , 2005]. Fortuna also suggests that size has a directly proportional relationship with vigilance and so as smaller juvenile pups are smaller they are less vigilant. Although they provide a lower calorie intake for the predator they are a distinctly easier catch.

4.6 Mobbing

Mobbing is a technique rarely employed by any prey but can have one of the most successful results for a group. Mobbing happens when a group of prey become aggressive against a stalking predator who they believe is close to attacking or successfully predating a member of the group [R Johnson et al, 2008]. Mobbing is a risky strategy for those involved but alerts other groups, individuals and juveniles of the predator's presence and eliminates any element of surprise or premeditation in the predators attack. This was a very successful strategy undertaken by Australian fur seals [Marine Mammal Science, 2005] although it was never witnessed at Seal Island amongst Cape fur seals.

It is clear now how individual predators and prey in this ecosystem behave, react and successfully predate and evade predation as well as some of the strategies they use collectively to complete these objectives. It is important to understand how this can be represented in a computer for the basis of the simulation to be proposed and how the decision tree and action process proposed can be applied to these virtual representations of individual animals or "agents".

5. Animats, Agents and Simulations

The term ‘animat’ is used to collectively represent an animal and an autonomous-robot [S W Wilson, 1987]. An animat is a representation of an animal such as a white shark in a virtual environment, where the behavioural patterns, learning capability, internal states, survival motivations, environment and social interactions and survival instincts are defined by the animal the animat is representing. In this case there are two animats in the simulation with defined animals as the white shark and Cape fur seal respectively, each individual instance of an animat in the simulation is an example of an agent.

An agent based simulation uses agents that are individually defined as a “self-contained entity” [J Dean, 1998] that is autonomous in its processing of inputs and task and when its behavior is defined by animal behavior based in an interactive environment, it becomes an animat. The theory behind the animat artificial intelligence is based on an agent (or multi-agent) artificial intelligence system [J Dean, 1998]. Animats behave according to their environment. From this you can see how animats are based on the theory of agents but based in an environment.

All agents (and therefore animats) have a state [J Dean, 1998] which affects the agent’s behavior and dynamics which determine the state and state changes. The complexity of the agent’s state and subsequent behavior is completely flexible as introduction of learning, motivation and instincts effects the states and state behaviour of agents. This idea is known as a bottom-up approach where you start with the basic competencies and build complexity from these. Three from the seven features of animats described by Dean may lend particularly well in this case study; behavior based architecture (as we are study the behavior of white sharks), real-time processing (applicable to all environment simulations) and an emphasis on learning (applicable to white sharks ability to learn prey movement). Multi-agent systems are simply a fixed environment (based here on the Seal Island ecosystem) with multiple agents. This adds another dimension of complexity as animats in a multi-agent system are reactive to the environment as well as other agents. A simulation based on the Seal Island ecosystem is clearly a multi-agent environment.

The idea of the animat, since being introduced by Wilson in the 1980s, has since still been a tool for proposing solutions or backing up theory rather than an outright proof. This is due to the fact there is no physical link or proof between neurological thinking and learning and artificial intelligence (in this case in animat’s artificial intelligence). Therefore as the proposed simulation will show the white sharks ability to learn from its prey and premeditate its actions accordingly, there will be no outright proof from the findings. It has been shown [C W Reynolds, 1987] how important graphical representation is in the simulation of agent-based systems as visual alternative to the importance of simulations when there is no hard and fast evidence or proof. Animats are helping to bridge this gap however as attempts to connect neural evidence to animats by collecting multi-electrode arrays of neural information to culture a neural network and mapping its activity to a virtual animat [T B DeMarse et al, 2001].

Animats can be used under experimentation through two methods with basic differences [J A Meyer at al, 1995]; either have fixed and defined behaviour inbuilt or have behaviour dependant on processes mimicking individual intelligence. We are investigating the issue of premeditative shark attacks on seals through a spatial means and through learning of the pinnipeds evasive strategies, both theories that involve the idea of learning. So to address the first defined category of premeditation through spatial recognition, a multi-agent based simulation of individual shark animats that shows a collective learning of successful spatial areas of predation would give strength to the theory. Further to this, by modeling the dynamics of the animats on the raw data collected by Martin on white shark behaviour, as well as the agents of prey on Cape fur seals, any correlation between the patterns of spatial shark congregation observed and recorded in Martin's findings with those produced by intelligent white shark animats would further strengthen any results.

5.1 Neural Networks and Spatial Learning in Animats

In order for the animat to learn about its orientation and spatial surroundings it must have a neural network by which it orients itself. Based on the previously presented idea that fish can learn about areas through instincts and emotions evoked by stimuli in certain areas which is then stored in long term memory, a neural network should be drawn up against this basis of these above rules combined with the idea of exploration for continual learning and discovery of new spatial areas. Based on Barton and Sutton's neural network for a similar theory where orientation is based on increasing and decreasing odours from landmarks dependant on distance, below is a neural network for the learning of spatial areas in relation to successful predation;

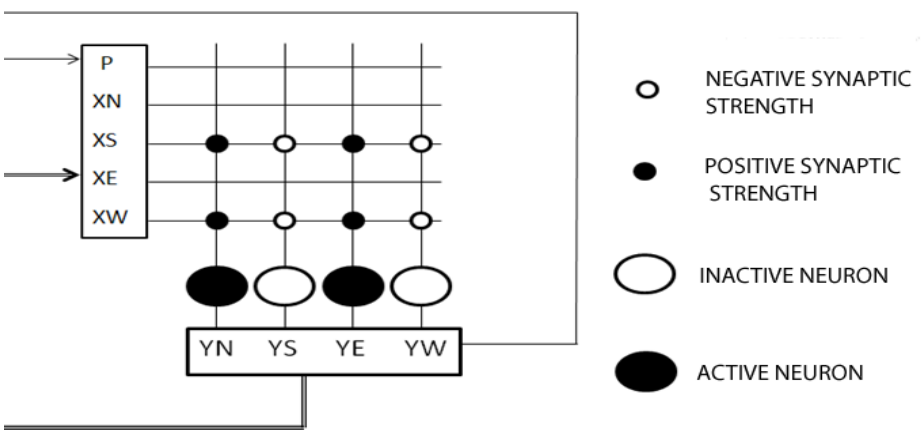


Fig 3 A Proposed Neural Network

The direction of the animat is defined by this neural network and the specific synaptic inputs which in turn tell which direction to move by activating certain neurons. Depending on the values of the inputs (XN...XW) with the reinforcement signal [A.G Barton et al, 1981] P, which is either a positive or negative value which the animat wants to maximise, specific output signals are produced (YN...YW). In the example above a negative predation value is given with the input directions of SW, this causes negative synaptic strength on these output direction and positive synaptic strength on the converse directions, causing two active and two inactive neurons making the animat change direction from SW to NE. There is also a random element that is considered when making neurons active or inactive, which is defined as the animats need for exploration which is required for the animat to discover new areas and for cognitive growth and learning.

5.2 Simulations

A computer simulation is an accurate means to provide an alternative and accurate view of certain environmental variables. The conundrum faced by many researchers and zoologists is the difficulty in tracking, monitoring and observing white sharks. The difficulty lies visually and physically, as humans are not aquatic creatures there are obvious physical barriers and time constraints when wanting to capture raw data on a large time scale in an environment that is largely uninhabitable and expensive to explore. When you combine that with the volatility of studying a creature who is a naturally aggressive predator to humans and notoriously difficult to capture and contain safely [Monterey Bay Aquarium, 2008] you have a lot of barriers to overcome when studying such a creature. Previous attempts to study white sharks are based on data mostly collected from stomach contents or visual recollection although recent technological advancements have meant a variety of new means of study and data capture, [A P Klimley et al, 2001] using radio-acoustic positioning based around radio signals transmitted from fixed positioned buoys to track tagged sharks. Although simulation is not an alternative to viewing or capturing raw data from the world it is a means of exploring and comparing predicted behaviours or factors that are difficult or impossible to track in the wild.

Agent-Based Modelling or Agent-Based Simulation is the means of representing agents or in this case animats virtually as a simulation. As we are modelling a multi-agent ecosystem we are therefore creating a "complex system", where a large number of agents are interactive and responsive to each other [Y Ando, 2005]. 'Boids' is one of the first and most successful multi-agent-based models on natural science [C W Reynolds et al, 1987] combining individual agents with individual movement rules governed by the positions of its fellow agents, the rules were such that the graphical representation of the agents showed a recognisable flocking movement of birds or schools of fish in the natural world. This is an example of how simple rules in a multiple agent-based modelling system can have such profound results without any learning or cognitive complexity. It is also an example of how important the graphical representations and output of the simulation are to the validity of the results, as previously stated simulations are not often seen as proofs, so the legitimacy of the results can often only be seen visually. This must be taken into account when choosing a modelling language to write the any simulation when deciding how important the graphical output of the simulation is.

A simulation that is recreated physically using robotics is said to require "specification of environment, needs, sensory and motor equipment, and learning method" [S W Wilson, 1987]. As the virtual world does not contain the constraints of the physical world we can discount sensory and motor equipment. However, the other variables are relevant; the specification of the environment is that of Seal Island referenced by Martin, the needs of the white shark are to successfully predate and the learning of the white shark animat is specified in the previous section. Laroche uses a simulation to indicate that behavioural actions of seals are inconsistent between age groups by comparing results of predation on adult seals and pups when behavioural strategies of pups fluctuate between risky and similar to adult seals. Then he compares the results to the actual findings of Martin. This does confirm that pups do have riskier behavioural strategies and are indeed more readily targeted by predators because of it. Similarly I want to use a method of results comparison with actual data collected to confirm or dismiss the idea that white sharks can spatially learn their environment to premeditate attacks on seals. The results will be in the visual form of where the white shark animats predominantly orient themselves when hunting as well as statistical data of how long animats stayed or ventured, allowing easy comparison to Martin's statistics on shark distribution. The particular comparison of interest will be the number of predations occurring in each sector of the surrounding sea area, as Martin breaks these sectors into 6 and records the total number over the three year period, this will be the basis of comparison as to where the intelligent and basic shark agents are predating seals.

6. Summary

I now want to summarise the findings and predictions made in this report and how the knowledge gained from this report will lead to the next stages of the project; the software requirements and evaluation, design ideas and development and the implementation.

When understanding the concept of premeditation a natural categorisation is made three basic categories by which premeditation can be defined in this context and then choosing to investigate the first category of the proposed ideas which was defined as follows; “The prediction of spatial areas and time periods where predation is highly likely or most likely to occur within an ecosystem”.

The simulation proposed will be based on Martin’s findings where the supposed premeditative attacks were witness but where the first substantial study of white shark and pinniped behaviour has been recorded and collated, which makes it the perfect basis for modelling and comparing experiment results.

Using Topal’s study of learning in paradise fish as a basis for the proposed explanation of how white sharks can learn to premeditate attacks, white shark predatory strategies were examined and a decision tree formed. The decision tree (*Fig 1*) of how white sharks come to attack is the result.

After looking at the palatability test, the actual predation process of pinnipeds in particular was looked at from a white shark’s point of view. The 3 phase diagram (*Fig 2*) of the attack process on a pinniped was then produced. The importance of the pinniped defensive mechanisms and predation avoidance was then looked at discussing tactics such as fleeing, flocking, grouping, mobbing, experience and vigilance.

Understanding the dynamics of the white shark and pinniped interaction then lead to the representation of these interactions virtually through animats, and how this could lead to a learning simulation using a neural network (*Fig 3*).

From understanding how animals are represented virtually lead to understanding how this can help show how white sharks can learn as virtual agents through their environment and with other prey agents, discussion of how this can be used as a simulation followed. Showing how previous simulations have been used as a means of comparison to raw data can help solidify a hypothesis in the hopes that similarly the simulation created with the white shark and Cape fur seal animats will bring similar results.

The next stage of the project involves designing rules and methods of defining and creating the animats using a simulation system, based on the rules that were defined in the investigation into predatory and evasive behaviour explored. These will be with the intention of implementing an ABM simulation that satisfies specific functional and non-functional requirements that have to be defined. Each area of behavior will be looked at in detail and represented as accurately as possible whilst still only maintaining the relevant areas of behavior. Experiments will then be formed from which results will be obtained and analysed.

Part II
Development

7. Requirements and Specification

The following section attempts to define exactly how the ABM simulation should operate at both a functional level and at a user level so that the subsequent implementation fulfils all expectations and results are generated are accurate to the highest possible extent. It should also ensure that the simulation is unequivocal to the user and that all results generated are unambiguous. Each requirement makes a point of exactly what the simulation should achieve which is then coupled with a bullet point providing an attempted answer as to how the simulation will achieve the requested requirement. Successful definition of requirements and specification should lead to greater success at the testing phase and reduce the likelihood of design flaws and logic bugs as well as increasing the likelihood of successful validation. User requirements are tested in the black-box testing whereas all functional requirements are tested in the white-box testing.

7.1 Non-Functional Requirements

The following list of non-functional requirements are not specific to the functionality of the simulation and all should be satisfied without any knowledge of the programming of the simulation;

- **The simulation must be written in a language suitable to fulfill all non-functional and functional requirements**
  - The simulation will be written in NetLogo which has proven to be the most suitable language for usability as it allows users familiar with NetLogo to interact with some of the variables only accessible in the code whilst providing a very clear and simple interface suitable for users with all levels of familiarity with NetLogo. NetLogo 4.0.4 also provides the necessary 2D graphical environment and contains many useful built-in functions (e.g. loading in a jpeg as an environment, link agents for seal grouping) that aid the transition for a real life ecosystem into a virtual environment.
- **The simulation must be usable to users familiar with NetLogo**
  - For users familiar with NetLogo the simulation will be very easy to use and run, the simulation is opened as any other using the 'Open' function in NetLogo, with the added instruction to save the environment jpeg in the root drive. There are also suggestions for experienced NetLogo users to alter variables in the code where appropriate and the consequent outcome of the results that may occur from this.
- **The simulation must be usable to users unfamiliar with NetLogo**
  - Once the simulation file SharksAndSeals.nlogo is opened in NetLogo there is an 'Information' tab to give full and comprehensive instructions to the user on how to use the simulation and the motivations behind the simulation as well as instructions on interpreting the results.
- **The simulation must have adequate documentation for all users to understand the simulation and understand how to successfully use it**
  - All documentation is in the 'Information' tab where all instruction, motivation and interpretation of the simulation and the results are present.
- **The simulation must always terminate once started**
  - The simulation is built on a 'per-tick' basis, where a 'tick' is a full turn in the simulation. Every tick represents each agent in the simulation concurrently running through its appropriate behavioural model. In simpler terms, each tick represents one movement of each agent. When a tick limit is reached, the simulation will terminate.
- **The simulation must run with an acceptable speed and terminate within an acceptable time**
  - The simulation runs on a 'per-tick' basis so the tick limit will be suitably low number so that each run of the simulation will be of suitable length. The speed is dependant on the complexity of the programming behaviour models of the shark and seal respectively, however NetLogo has an inbuilt time alteration slider allowing for suitable 'speed-up' or 'slow-down' of the simulation.

- **The simulation must be have user controlled variables that do not restrict other non-functional requirements**
  - The user controlled variables in the simulation are the number of shark agents, the number of seal agents, and a Boolean switch of shark intelligence. The range of inputs for each is 1-100 for the shark and seal agents, and on or off for the shark intelligence switch. This prevents negative or inappropriate user inputs and ensures that the simulation will run regardless of the user input.
- **The simulation must display suitable results after each termination of the simulation which must be easily interpretable**
  - The total number of predations is displayed in a monitor as are the number of predations for the individual sectors. There is also a monitor for the number of predations occurring on the border between land/sea or between each sector. The interpretation of the results is described in the Information tab.
- **The simulation must output a set of results after each termination of the simulation**
  - The predation results are outputted visually in the interface as well as the percentage of predations for each sector being outputted in CSV format once the simulation has terminated.

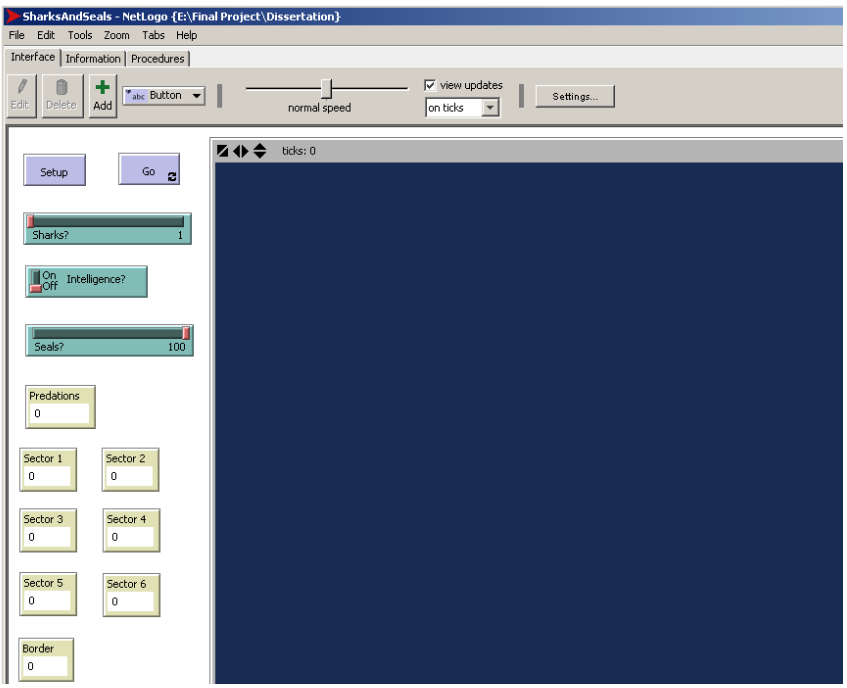


Fig 4 – The user interface of NetLogo with user controlled variable settings

The non-functional requirements listed represent the basic requirements that the simulation needs to fulfill, the functional requirements provide a low level insight into the specifics of NetLogo. Each of these requirements comes under the umbrella of the key non-functional requirement of the simulation;

- **Provide an accurate simulation of Cape fur seals and white sharks in the Seal Island ecosystem, where white sharks predate seals and each predation occurs in a defined sector (1-6)**.

This is a broad non-functional requirement and the most fundamental, therefore the provided answer to this requirement will be the following set of functional requirements that collectively answer this requirement.

The agent based universe in NetLogo consists of four different agent types which make up the moving agents and the environment in which the simulation is created. The four agent types are patches, turtles, the observer and links. Turtles are the moving and interacting agents in the environment, the patches are a matrix of static agents to comprise the environment boundaries and features, the observer is the overseer with the ability to create new turtles and links are static agents created when two turtles interact [NetLogo 4.0.4 User Manual, 2009]. A further explanation is necessary to understand how each fits in within the context of this simulation.

7.2 Patch Agents

Patch agents are the static agents that compose the environment on the drawing level of the simulation; this will be the background environment of Seal Island and the surrounding waters in which the white sharks predate. This is a fixed environment in which the shark agents will be contained and the seal agents will be able to join the environment from either edge, there will not be wrapping included on the map however as a seal agents exit the parameters of the outer patch agents they will terminate and leave in a state of "hidden" and the seal agents will eventually return, coming toward the island. The matrix of patches will be a 212 by 264 patch matrix around the origin, ranging from -103 to 103 x axis and -132 to 132 y axis. Martin uses the numbered sectors below to identify where in relation to the island an attack takes place and directly from this diagram the environment has been interpreted into NetLogo using the same boundaries only with coloured patches as identification of boundaries. Once these colours have stored a variable of sector number to each patch (or as a land patch) then the colours will be blended as one to create a more aesthetically pleasing look, whilst still recording a sector number when any successful predation occurs on any sea patch.

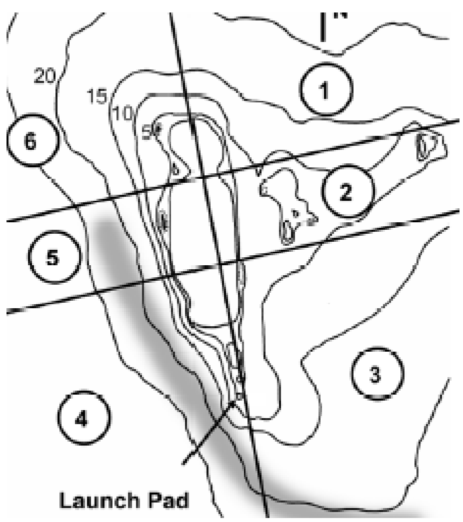


Fig 5 Seal Island [R A Martin et al, 2005]

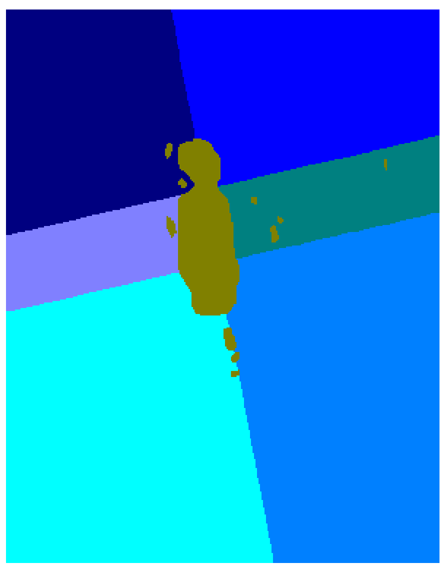


Fig 6 Seal Island Interpreted into NetLogo

7.3 Patch Agent Functional Requirements

I will now attempt to list the function requirements of the patch agents in the simulation and how the implementation will account for this;

- **The patch agents will accurately represent the environment of Seal Island in terms of scale**
  - NetLogo function import-pcolours imports an image and scales this down to fit the patch agent matrix
- **The patch agents will accurately represent the environment of Seal Island in terms of intractability with the turtle agents**
  - Importing the environment onto the patch matrix means that barriers of patch co-ordinate, patch colour or other variables can determine how a turtle agent interacts with its surrounding e.g. white shark agents cannot move to beige patches as this represents land mass
- **The patch agents will provide accurate barriers to turtle agents**
  - The topology of NetLogo allows setting the environment to a box (non-wrapping vertices) rather than a cylinder or torus which gives patches on an edge a smaller number of neighbours. When this is coupled with the rules of turtle agents becoming 'hidden' or to 'die' then agents can be seen to leave and re-enter the barriers of the environment as if in real life.
- **The patch agents will provide accurate measure of distance from the origin**
  - Each patch agent contains a co-ordinate from the origin which can be calculated in distance by any other patch or turtle agent.
- **The patch agents will provide accurate representation of a sector of the environment**
  - Each patch agent contains a sector variable with a number between 0 and 6, where 1 to 6 represent defined sectors as shown in *Fig 5* and 0 represents land, uninhabitable by shark agents

7.4 Turtle Agents

Turtle agents are what are typically thought of when thinking of an agent based simulation or any form of agent. They are the moving and interacting component by which data is gathered and consequently results are formed. They are the agents which can be born, die, reproduce, eat, move and do anything that a real living agent can in a simulation. In NetLogo they interact not only with patch agents to navigate their environment they also interact with each other forming link agents. Our experiment focuses on predation so few of the previously mentioned cycles of an agents life are required for instance reproduction is not concerned as the population of either species is not being measured, neither is consumption as predation is merely calculated by the recorded percentage of likelihood with either a predation or an escape. All that is really needed then is the initial creation of the turtle agents and the death and movement of the agents. What will hopefully emerge are the patterns of successful predation and the movement patterns sharks when programmed to remember the areas of predatory stimuli from past experiences compared to when the sharks are programmed to navigate with pure curiosity instinct. What is key to achieving both these goals is the distinction between turtle types (shark and seal) and the surrounding vision and awareness of a turtle agent.

NetLogo allows you to specify breeds of turtle agent which allows definition of the white shark and Cape fur seals as the two turtle agents; shark agent and seal agent. The behaviour of both will be very different as sharks will be able to navigate only certain areas of the map and cannot leave the borders of the environment seals can navigate land and sea and objectively seek to leave the map in groups when not resting ashore as well as returning from outward bounds. There is a possibility of introducing a third group of agents; seal pups. As Laroche has shown with his simulation that pups are an easier target for white sharks and affect the predatory tactics of a white shark, which would introduce an interesting element [R K Laroche et al, 2006]. However, as the main focus here is the predation and the area of predation rather than the prey itself, and therefore the seal agent will contain a variable of its age which will allow avoidance of creating a third separate turtle agent breed.

Fig 7 A Shark Agent in NetLogo

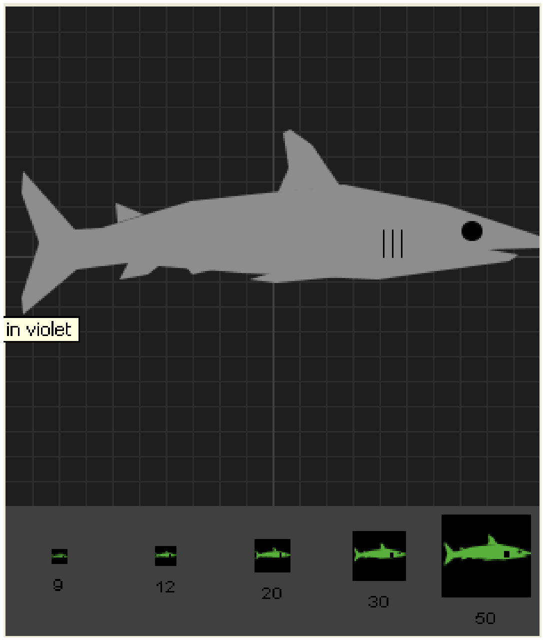
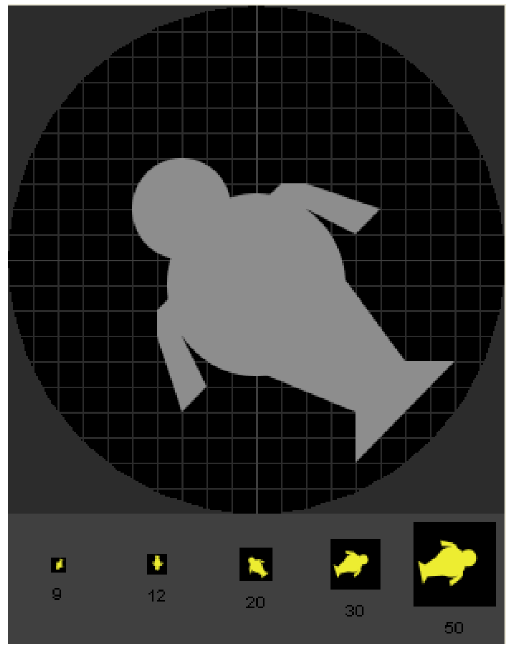


Fig 8 A Seal Agent in NetLogo



7.5 Shark Agent Functional Requirements

I will now attempt to list the function requirements of the shark agents in the simulation and how the implementation will account for this;

- **Shark agents must be able to predate seal agents only**
  - The turtle agent function to eat, and subsequently for the seal agent to die when a link agent is created between a shark agent and a seal agent.
- **Shark agents must not be able to leave the patch agent matrix**
  - The patch matrix will be boxed to avoid wrapping and no further rules are therefore needed for the shark agents to navigate.
- **Shark agents must be able to navigate in water areas of the map**
  - Shark agents will be able to navigate anywhere on the map that is blue as using colour as a differentiation between the water areas of the environment and the beige colour as the land. NetLogo allows colour distinguishing barriers within the patch agents which is useful in this case as there are only two differentials in the environment.
- **Shark agents must be able to have basic navigation**
  - The sharks with basic navigation will have a curiosity variable which will push the shark in new directions as well as the overriding navigation toward a seal within its vision to initiate predation.
- **Shark agents must be able to have intelligence**
  - Intelligence is a key variable that will store co-ordinates of a predation within a shark agent using a local variable and will influence the direction of the curiosity variable causing the shark to tend toward previous areas of predation.

- **Shark agents must be either intelligent or basic**
  - A switch to give all shark agents intelligence or basic navigation will allow the intelligence variable to be switched on or off.
- **Shark agents must be able to predate or fail to predate a seal agent during an attempt**
  - Success of predation will have the following factors, age of the seal, size of the group, location of the predation. The results of this will determine the percentage of success or fail to be calculated based on Martin's results and findings. Failure results in the seal continuing its navigation success results in the death of the seal.
- **Shark agents must be able to navigate with an element of curiosity but with an overriding necessity to predate.**
  - When there are no prey within the vision of the shark agent then the curiosity variable will guide the shark to new locations whilst there is no prey within site, as prey is encountered the shark will navigate towards it overriding and option to navigate elsewhere.
- **Shark agents must have some sort of vision to represent real shark optic vision**
  - Shark agents will be able to identify and analyse 2 patch agents surrounding its current location

7.6 Seal Agent Functional Requirements

The seal agents will be harder to model than the shark agents as they are not as linear as the shark agent, simply because the seal agents have no real purpose other than to survive. The survival techniques of the seals detailed under section 4 are not all included in this model as that is not the focus of the model, however continuity and accuracy is still essential. Therefore grouping is included in the behaviour as this is an essential part of the seals leaving and arriving on the island and is included in Martin's statistics of successful predation; using these statistics will therefore affect the outcome of individual predation and each seal. The other main difficulty faced with the seal agents is their ability to seamlessly leave the environment and return at different times. This will need to be implemented on randomly allocated ticks or by randomly choosing to stay static.

I will now attempt to list the functional requirements of the seal agents in the simulation and how the implementation will account for this;

- **Seal agents must be able to be predated and therefore die**
  - If the outcome of predation is calculated as success then the agent will be commanded to 'die' and therefore disappear off the simulation. There are no rebirths and once all the seals are predated the simulation is over.
- **Seal agents must be able to navigate across the environment of the simulation**
  - The basic navigation of the seal will be different from the curiosity instinct of shark with intention to predate. The primary instinct is to remain on the safety of the shore, secondary is to travel offshore out of bounds the third is a curiosity instinct to explore the sea. Each individual action will be calculated on the percentage of each instinct.
- **Seal agents must be able to navigate outside the environment and become “hidden”**
  - Patch agents within the box formation have less than eight surrounding patches, therefore with the sight of the seal agent when detecting it is going into a non-existent patch it can define its state as hidden and reappear after a certain amount of ticks.
- **Seal agents must be able to form groups and navigate in groups**
  - Seal agents that selected to travel offshore can 'tie' other seals until a fixed number of seals in the group are tied and follow the lead seal, a number that will be selected in line with Martin's findings of group size and frequency.

- **Seal agents must have a preference to land dwelling with sea dwelling as a secondary.**
  - The primary instinct is to remain on the safety of the shore, secondary is to travel offshore out of bounds the third is a curiosity instinct to explore the sea. Each individual action will be calculated on the percentage of each instinct
- **Seals agents must have an accurate likelihood of surviving predation as that displayed by Martin**
  - Success of escaping predation will have the following factors, age of the seal, size of the group, location of the predation. The results of this will determine the percentage of success or fail to be calculated based on Martin's results and findings and the outcome will be calculated on this percentage.
- **Seal agents must have some sort of vision to represent real seal optic vision**
  - Seal agents will be able to identify and analyse 2 patch agent surrounding its current location.

7.7 Link Agents and The Observer

The observer is an agent that is defined by its name, an observer. The observer agent is just something that overviews the model and can control turtle agents and other model variables. By this standard there are several requirements that the observer has to meet from the user's perspective of the model. The link agents are agents that form with two endpoints between two individual turtle agents, they cannot effect the patch agents or turtle agents however and they will not be used in this model. They could be used in theory during a predation to create an effect of predation but this would be just to enhance the visuals of the model and reinforce the idea of predation taking place to the observer.

7.8 Observer Functional Requirements

- **The observer will be able to alter the population of the shark agents**
  - A slider will be provided to alter the population of the shark agents prior to setup.
- **The observer will be able to alter the population of the seal agents**
- - A slider will be provided to alter the population of the seal agents prior to setup.
- **The observer will be able to view the number of predations**
  - A monitor will be provided to provide a counter for the number of successful predations.
- **The observer will be able to view the number of predations within each sector**
  - A monitor will be provided to provide a counter for the number of successful predations for each sector of the environment.
- **The observer will be able to turn the intelligence of the shark on or off**
  - A switch to give all shark agents intelligence or basic navigation will allow the intelligence variable to be switched on or off.
- **The observer will be able to start the simulation and restart after it has halted**
  - The observer will be able to start the simulation using 'Go', once halted after a certain amount of ticks the simulation can be reloaded using 'Setup' after the desired variables have been set, this is then repeatable.

8. Implementation

The accuracy of the implementation of the system is directly proportional to the accuracy of the results and therefore the validity of any results obtained. To make the implementation as accurate as possible means to make it as realistically modelled on the real world as possible in the areas that are possible to imitate and within the scope of the experimentation and the boundaries of NetLogo. This simply means making the areas of the simulation that are important and relevant to what is under investigation as accurate to real life as possible without including unnecessary functionality or going into unnecessary depth. So if a function of the real world is related to the white shark's ability to premeditate attacks on Cape fur seals it has to be evaluated as to its relevance on this experiment. The experiment itself is investigating the white shark's ability to remember key spaces of previous attacks to launch premeditated attacks and therefore if a real world function is to be included it must be done so with the highest accuracy with reference to real world statistics, constants or variables as justification. Where there are new realms or boundaries being explored then probabilities must be taken with some accurate estimate or failing that randomisation.

To explain how the simulation is implementation the firstly definition of the constants of the simulation is required with relation to satisfying a requirement. These can be categorised under seal, shark and environment. These are the three key categories that make up the three interactive elements of the simulation and expanding on each of these areas should lead to a better understanding of the proposed behaviour of each of these interactive categories and a better understanding of how this behaviour leads to the interactions between each agent of the simulation. With justification from real world findings and articles this will help to ensure accuracy in the behaviour of each key category and where this cannot be found then an accurate and justified estimate will be used, lastly if this is still unattainable randomisation will be used.

8.01 Excluded Areas

There is no feasible way to create a simulation in any language to represent a simple predator/prey ecosystem that encompasses every variable, constant and element of a real life scenario. By this definition simulations are not proof of findings, just a possible representation and therefore variables of the scenario in question must be handpicked by the designer of the simulation. All (or as many as possible) elements that are relevant must therefore be included and represented as accurately as possible. Therefore to justify what areas are included first recognition of what elements are excluded and the justification for this is necessary.

The restrictions of the NetLogo language are its lack of high-end technical graphics, as this is a statistically centred simulation without any real reliance on high-end graphics, the idea of a detailed graphics and the idea of depth in the simulation become irrelevant. There is an option to use a 3D view on NetLogo which would be relevant if one of the variables in consideration was the measurement of sea depth in which the predations took place as this would require a 3D environment. The depth of predations or shark movements are not under consideration in this simulation, as the spatial consideration is in reference to Martin's six sectors as defined in *Fig 5*, although there are recordings of at which depth certain attacks occurred they are predominantly surface attacks. For these reasons the seal and shark agents will operate on a 2D environment that is sectioned into land and sea, where the sea is sectioned into Martin's six sectors of predation.

The interaction between shark and seal is not under strict scrutiny in this simulation, once a predator and prey are assumed to be in predation then the outcome of the attack will be simply a calculation of the likelihood of success based on certain factors. There are many other variables that could affect the outcome of a predation such as the age of the seal or shark [R K Laroche et al, 2006], the energy of the shark, the wellness of the seal, the size and speed of the seal and shark etc. These will be ignored due to the lack of relevance in relation to the areas of predation. While it is important to represent the behaviours of the seals and sharks accurately this level of interaction is too low-level and therefore irrelevant, whereas the outcome of the predation in relation to where the predation occurs (most likely in areas close to shore, least likely in far out deep sea) is clearly a variable to factor in.

The term 'frolicking' will be used to encompass the seals alternative to resting on the shore, travelling away from the island or returning to the island. These four activities are detailed by Martin as the main activities of the seal behaviour, where 'frolicking' here is an umbrella term where the seal will be fishing, playing, thermoregulation or competing for space [R Johnson et al, 2008]. This is to generalise the areas of behaviour of the seal that are not specifically relevant to the areas in which predation occurs.

8.02 Included Areas

Looking from the converse perspective there are some areas where inclusion is mandatory, when considering the behaviour of the seal the four main activities as previously defined will be included but a closer look at the extent at which the defensive behaviours of the seal need to be included is needed. As previously mentioned the specific interactions by individual predators and prey will be simulated by probability so the flocking, fleeing and vigilance techniques are not relevant in this case. Grouping however is essential as the main activity of the seal is to either swim to or away from the island which would require a grouping technique, therefore the seals main means of transport is as a group. As seals leave and return the island in groups and are most often attacked during these two activities it is therefore essential to include this defence mechanism in the simulation. Mobbing is a rare occurrence amongst seals and can therefore be assumed as an anomaly as no occurrences were observed during Martin's three year observation. As there is no time-scale as a backdrop to the simulation (agents are not born, grow or age) then the experience of the shark or seal is redundant and therefore not used.

Shark behaviour is in many ways less complex than seal behaviour, mainly as their only activity among Seal Island is predation. There are two possible variations in shark behaviour which the simulation must accommodate; intelligent and basic. Whilst the names may have obvious connotations they are in fact quite similar, the intelligent behaviour must include the random behaviour (also seen as exploratory as part of the sharks curiosity instinct [A Miklósi et al, 1989]) and extend to returning to an area of previous predation(s) through some intelligent conclusion. Just how a white shark would decide upon when and where to return to an area of previous predation or positive stimuli is somewhat of an unknown and discussed later in the chapter. The random behaviour however must still resemble the search and hunt method of a shark without being overly trivial and whilst still maintaining some form of randomness to imply lack of intelligence. Therefore the basic shark agent will randomly choose a location on the map to travel to whilst still avoiding land obstacles and attempting predation if it happens upon prey, whereas the intelligent shark will do likewise but also return to previous areas of positive stimuli in the hope of repeating predation when a certain amount of time has passed since the last successful predation.

8.03 Constants and Variables

Various constants can be defined from what must be included in the simulation and from those areas that have been purposely included to aid the accuracy of the findings. They are defined with justification here under the three categories of interactive agent (shark, seal and environment).

Shark

- Range of visual awareness (distance) - **15 metres, [S H Gruber et al, 1985].**
- Speed relative to a seal agent - **25 mph top speed, 1.5 mph average**
- Average size relative to a seal agent – **3.5m to 5 m**

Seal

- Range of visual awareness (distance) – **12 metres**
- Speed relative to a shark agent – **1.37 average, [R R Ream et al, 2004]**
- Average size relevant to a shark agent – **2.3 metres**
- Average number of seals on seal island **- 36,000 - 77,000 [R K Laroche et al, 2006]**

Environment

- Total patch matrix size relative to the Seal Island ecosystem **- 1400m X 1700 m, equating to 212 X 264 patches**
- Scale of patch size to real life distance metric – **(1400/212 + 1700/264)/2 = 6.5m per patch**

From these constants some features of the simulation can be derived, most importantly that the shark and seal agents have a very similar average swimming speed. This means (adhering to the NetLogo design) during each iteration of the agents movement both shark and seal agents can progress at the same speed and distance except during the premeditative strike before predation as this is when white sharks increase to around their top speed, and in this case a shark will be able to jump two patches forward to imitate this increase in speed whereas the unknowing seal will continue at an approximate speed. Seals and sharks can have an estimated vision of two patches allowing shark and seal agents to have a similar cone of visual awareness as both also have a high degree of peripheral vision with side mounted eyes rather than forward facing. These constants also show how a sharks size is equivalent to one shark agent fitting on one patch of the environment, whilst this is not the case for the seal there is no way of altering the size of the agent to fit this anomaly. This will have to be taken into account when reviewing the conclusions and accuracy of any results that may be effected.

Various variables can also be defined from what must be included and from what has chosen to be included. Some variables have referenced justifications some variables are under investigation and will therefore be a part of the experimentation stage of the project and are therefore referred to as “to be examined”.

Shark

- The shark's choice of previous area of predation to return to - **To be examined**
- The ratio of the shark population to the seal population - **To be examined**
- How the energy level effects the shark’s choice of destination **- To be examined**

Seal

- Range of group size leaving the island - **group size 5-20, [R. A Martin et al, 2005]**
- Range of group size returning to the island - **group size 1-5, [R. A Martin et al, 2005]**
- Ratio of probability of the direction that seal groups leave and return to the island – **In order of rank from most frequented to least 4, 3, 5, 6, 2, 1, [R. A Martin et al, 2005] (tbe).**
- Probability of choosing which direction to leave the island **– To be examined**

8.04 Seal Agent Movement

An Agent-Based Model contains a series of agents where some are interactive and so are not. The two categories of interactive agents are the seal agent and the shark agent in this case. As interactive agents they are required to interact with each other, their environment and any other interactive agent which means they have a basic requirement of intelligence. The intelligence of this agent can be deduced as a serious of decisions with answers dependent on the variables within the boundaries of the simulation. These decisions can be expressed in a decision tree to give an overall view of the intelligence of an agent and each decision tree can be encapsulated as a module with a set of inputs and outputs, where a set of states determine how the modules (or functions) call each other. This section attempts to detail each module and how it reacts to the state that it is given, and how this will output a state depending on different variables in the environment. The following section will show how these modules interact with each other in a diagram form and explain how they interact iteratively. The last section will detail each module at a low level using decision trees.

Move Seal.
Functions: Detect whether the agent is currently visible (e.g. part of the simulation) or if it is hidden (e.g. beyond the bounds of the environment). Detect whether the agent is on land or sea. Detect whether the agent needs a new child function to be assigned. Assign a new child function. Allow continuation of previous child function.
Input States: Neutral, Neutral (Hidden), Frolic, Do Nothing, Travel Away, Travel Back, Form Group.
Output States: Frolic, Do Nothing, Form Group, Travel Away, Travel Back.

Lets Frolic
Functions: Determine if this is the first iteration of frolicking. Find a destination at sea to frolic. Wait 3 seconds. Repeat. Halt Frolicking. Set home as destination. Set travel back state. Move forward.
Input States: Neutral, Frolic. *Output States:* Frolic, Neutral.

Do Nothing
Functions: Wait in the same space for a fixed time. Halt Doing Nothing.
Input States: Neutral, Neutral (Hidden), Do Nothing. *Output States:* Do Nothing, Neutral.

Form Group
Functions: Form a group ready for travelling away by searching for seals with a Neutral or Form Group state.
Input States: Neutral, Form Group. *Output States:* Form Group, Travel Away.

Set Group Heading
Functions: Set a destination for the newly formed group to travel towards with a set bias probabilities where a direction chosen is firstly SW, secondly SE and thirdly and other direction.
Input States: Form Group. *Output States:* Form Group.

Travel Away
Functions: Move forward group in set direction, determine whether the agent is about to go out of bounds if so disband and become hidden.
Input States: Form Group, Travel Away. *Output States:* Travel Away, Neutral (Hidden)

Travel Back
Functions: Move forward group in set direction, determine if root agent (leader) has reached home if so disband and set all leaf agents as root agents and set their destination as home.
Input States: Neutral (Hidden), Travel Back *Output States:* Travel Back, Neutral

8.05 Module Tree Diagram

To better show how each module interacts with each other and how each state effects how a module calls another module (or 'function'), below is a tree diagram showing how each module is arranged hierarchically. If there is an arrow from a module to another that means that the module pointing can call the module it is pointing to. There are of course conditions and other variables that determine how a module calls another or what state to put it in. The current state will be shown accordingly as a module calls another. As NetLogo is an iterative language where each agent concurrently calls their own behaviour set per turn, a turn is always started at the top of the hierarchy and finishes when the tree terminates so it can be assumed as a bottom module calls downward it is returning back to the top module. The states roll over to the next turn as do all variables.

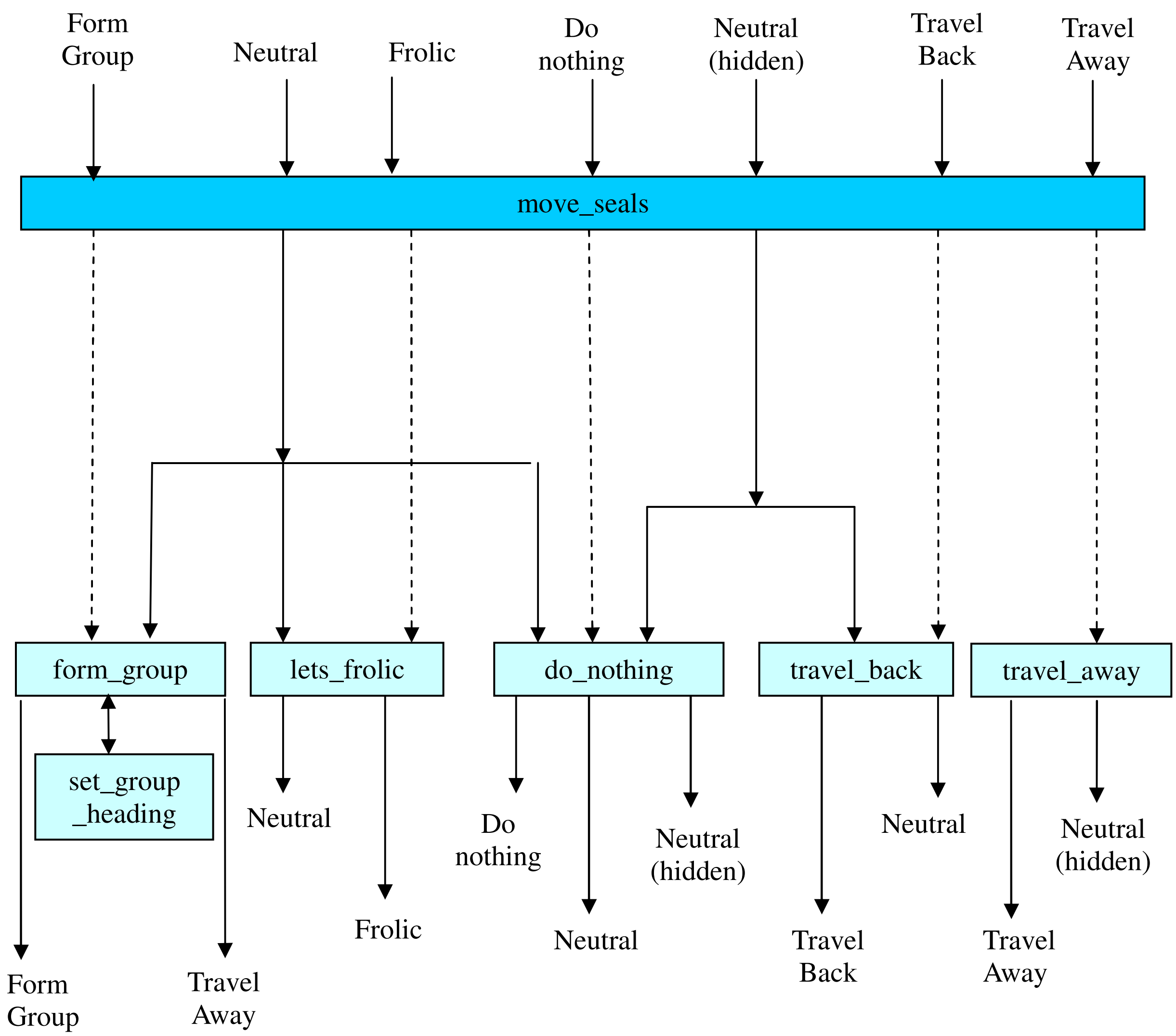


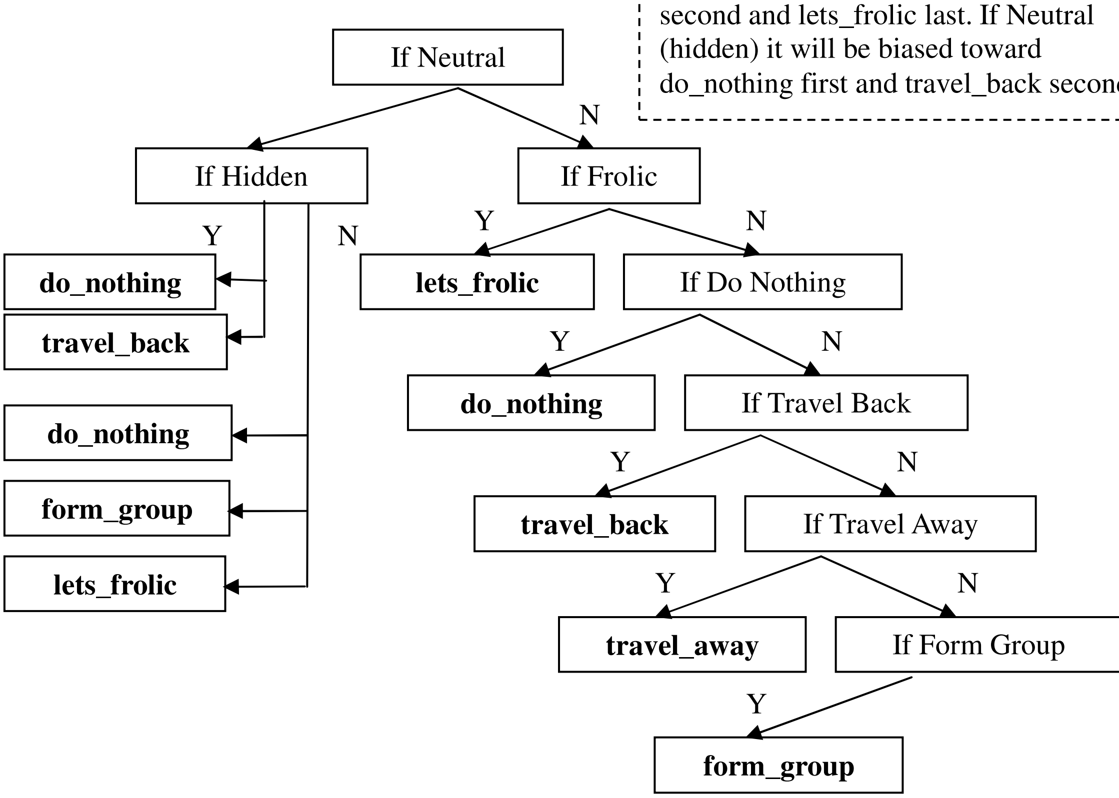
Fig 9 Module Tree Diagram

8.06 Module Decision Trees

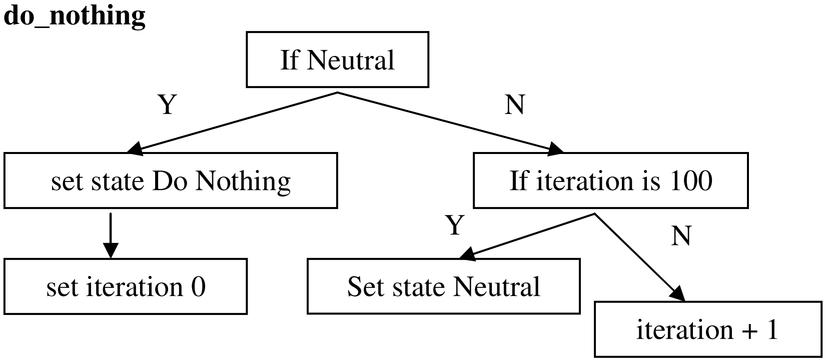
This section attempts to detail each module and how the current state effects which modules are selected to perform certain actions, this can be used in conjunction with the module tree diagram so that it is possible to trace the exact decision that goes into each 'turn' or movement of the seal. All modules are highlighted in bold and all states are capitalised. When there are multiple options without a clause then there is a random selection with a biased probability for each option. There is also a passive state that has gone unmentioned until now; when a seal is tied to another it becomes a follower within a group and its movements are completely controlled by the tie to the leader seal. This means any moves can be done only by the leader seal and all ties from this will pull all follower seals in the same direction, this is inbuilt in NetLogo. There may also be 'if' statements where only one option is continued, you can assume if the answer to the 'if' question is not this then the turn is over.

Explanation – The **move_seals** module determines which module to call from the seals' state. If Neutral it will be biased towards do_nothing first, form_group second and lets_frolic last. If Neutral (hidden) it will be biased toward do_nothing first and travel_back second.

move_seals

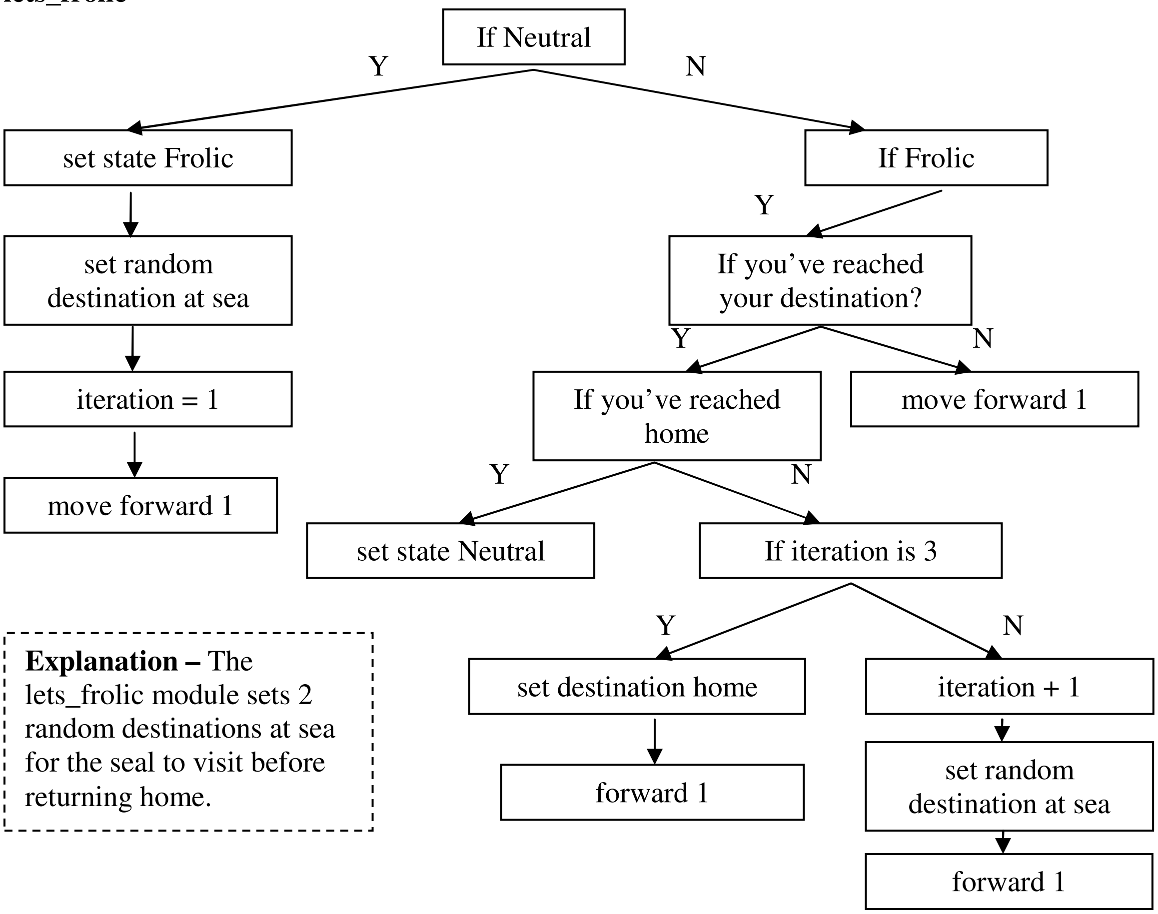


do_nothing



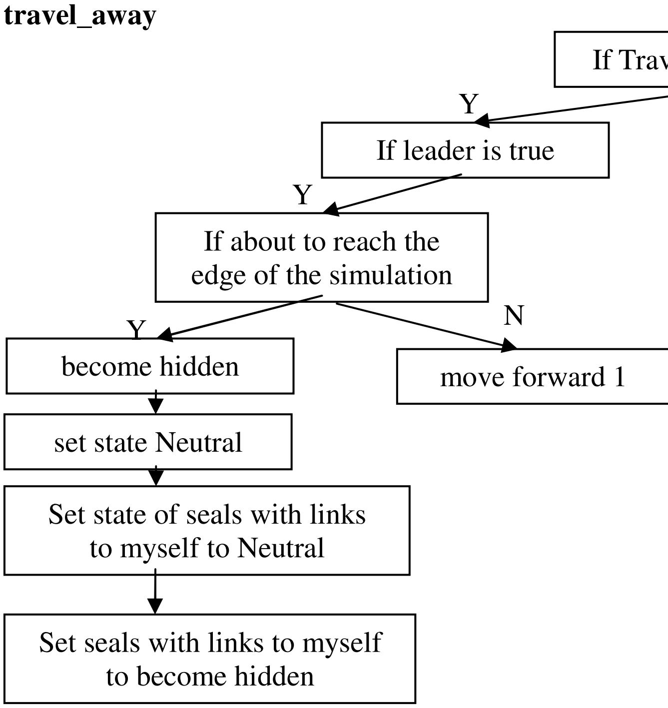
Explanation – The do_nothing modules is a simple iteration that increments 100 times before returning to a Neutral state, imitating the seal doing nothing.

lets_frolic



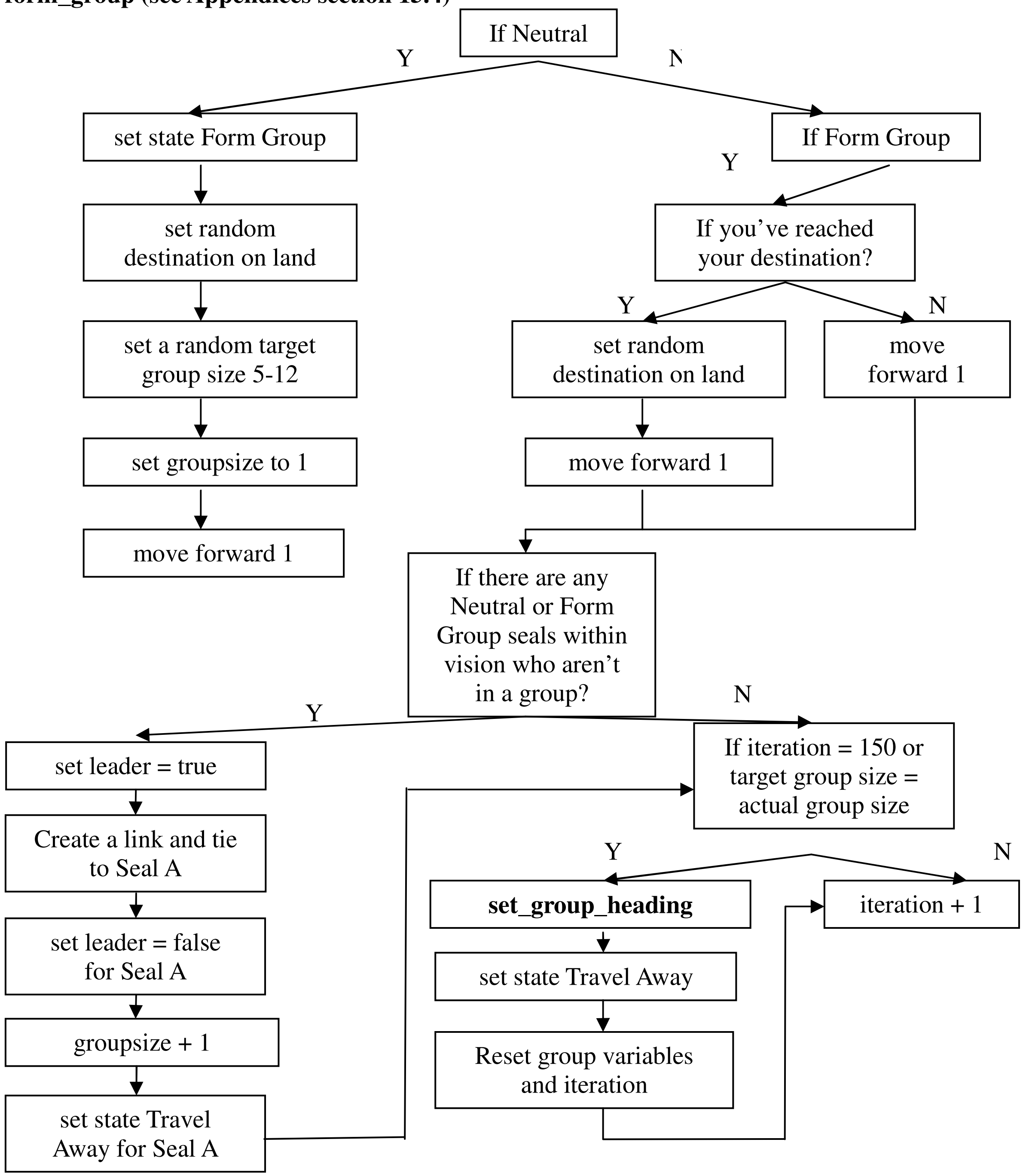
Explanation – The lets_frolic module sets 2 random destinations at sea for the seal to visit before returning home.

travel_away



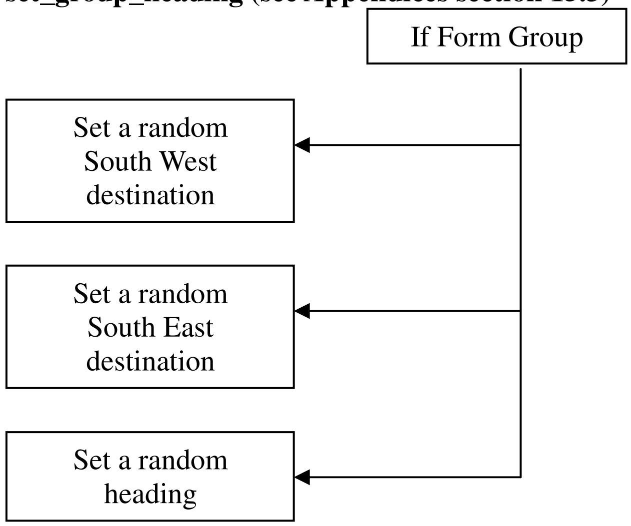
Explanation – The travel away module is used once a group has been formed and a heading set. At this point there is an established leader and multiple followers tied to it, who are passive. The leader heads toward its destination until it reaches the bounds of the simulation where it changes its state and becomes invisible, however the group does not disband. All seals are in a Neutral (hidden) state.

form_group (see Appendices section 15.4)



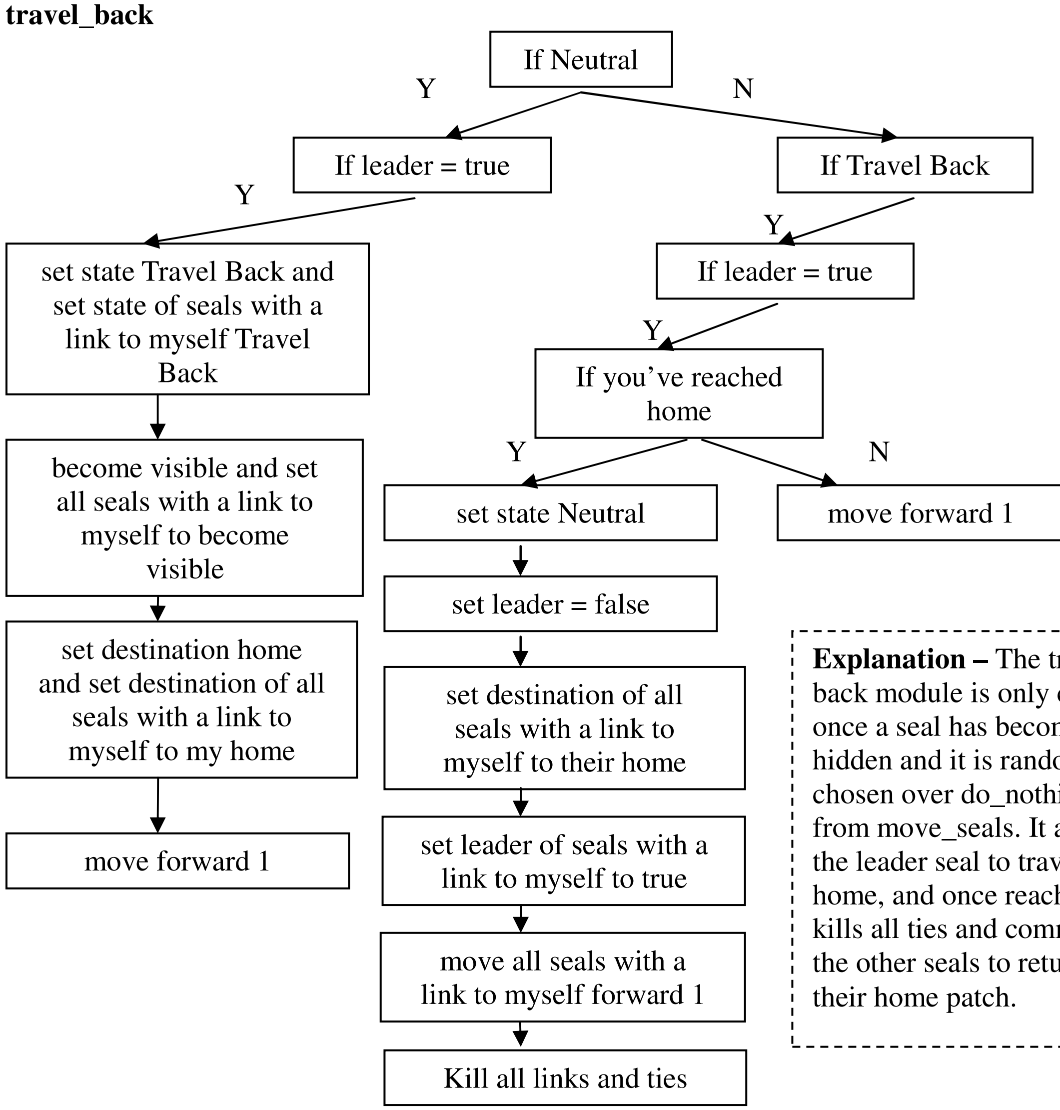
Explanation – The form_group will set a target groupsize and cyclically choose destinations on land and travel to them until the seal in question has gathered enough seals to fit its target or until the iteration counter has reached 150. This is to break any looping for finding seals for a group that don't exist.

set_group_heading (see Appendices section 15.3)



Explanation – The set_group_module simply randomly chooses a destination for the leader seal of a group to head. Its preference is SW, second preference is SE and third preference is random. This is in conjunction with findings on the seals actual preferences when leaving the island (R. A Martin et al, 2005).

travel_back



Explanation – The travel back module is only called once a seal has become hidden and it is randomly chosen over do_nothing from move_seals. It asks the leader seal to travel home, and once reached kills all ties and commands the other seals to return to their home patch.

These decision trees can collectively represent the behavioural model of all seal agents in the NetLogo ABM simulation. Each decision tree represents a module, and they are all inter-connected as individual modules as represented in Fig 9 Module Tree Diagram. This behavioural model can be followed for every turn or 'tick' of the simulation, starting at the top of module tree diagram, passing through each decision tree of the module. This design ensures complete transparency when transferring to the hard coded program. This is shown in the appropriate appendices of code for the individual module. This behavioural model is applied to every seal agent in the simulation; each agent concurrently goes through the behavioural model per 'tick'. Likewise, the shark agents concurrently run through a similar behavioural model per tick that allows them to navigate the environment, make decisions and predate seal agents.

8.07 Shark Agent Movement

The shark agent movement is less linear in design than the seal movement hierarchy however there are some similarities; each function can be looked at as a module with a hierarchy that is iteratively parsed through for each shark agent concurrently and each module can be deduced as a decision tree. However there is more embedded calling of modules from within other modules instead of there being one sorting module which calls the correct module in relation to the state of the seal. Instead there are no states for the shark agents, meaning that each agent goes through the same decision process and the difference in behaviour is determined by variables such as Intelligence?, the location of the shark on the map, the location of seal agents in relation to the shark agent and the current energy of the shark. The effecting variables are as follows;

Energy – This is a variable that represents the curiosity variable as described in the neural network that the shark agent is based around (*Fig 3*). It simulates a combination of the energy that the shark acquires after a kill and the subsequent need to feed again, resulting in a more curious shark when the energy is high and conversely a shark looking to return to a previous predation and increase the likelihood of feeding and increasing its energy levels. Energy decreases per turn and increases to a fixed level after feeding, there are some aspects of energy that have been left out of this simulation for their irrelevance to the experiment. A shark with a high energy level may be less willing to hunt immediately if an opportunity presented itself, however if a seal is within a shark agent's vision it will predate regardless of energy. Equally in reality if the energy levels of a shark became too low and the time since a predation too long it would die, this is not the case in this simulation. The reasons for these exclusions is that there is no fixed value or time known for a shark before it wishes to feed, and therefore this extra variable would be outside the scope of this experiment. Similarly there is no fixed constant value or time that can be placed on a shark for the amount of time before it will die of lack of energy and is therefore outside the scope of this experiment.

Intelligence? – This is simply a Boolean variable which is determined by the user in the user panel that determines whether all shark agents act with the intelligent navigation algorithm or with a basic navigation algorithm based on random neighbour patch selection. The both algorithms are destination based, meaning that sharks will navigate to a set destination and once reached set a new destination for itself, if Intelligence? is true this destination could be a past predation or a random new destination (depending on the energy variable) otherwise it will always be a new random destination.

Position of shark in the environment – Unlike the seal agents who can potentially travel to any patch on the environment shark agents are limited to sea patches only. This means that a simple instruction to move forward will break this rule; therefore depending on where the shark agent is on the map depends on which direction or heading the shark will take in order to reach its destination. The module move_forward is designed to deal with these complications.

Position of seal agents in the environment – The priority of the shark agent is to predate which means if a seal agent is within the shark's predatory vision it will always attempt to predate. After the successful or unsuccessful predation the shark will continue to its previously set destination, behaviour which has been previously observed [A P Klimley et al, 1989].

Iteration – A counter that causes a new destination to be set, if this is reached then for whatever reason the shark agent cannot reach its current destination and is in a loop therefore the counter resets its current destination.

8.08 Previous Predations

It has been shown that fish have a curiosity instinct which is overruled when in an area that is associated with a certain stimuli (fear of predation etc.) [J Topál et al, 1999] and that fish have the ability to hold long term memory [V Csányi et al, 1989], however it is not clear of the capacity of memory of fish, specifically how much can a fish brain hold in long term memory and this poses a problem as to how many areas of previous predation a shark agent can hold. It also poses the question of which previous predation a white agent chooses to revisit, and whether it visits multiple previous predations until it finds prey and whether these are ordered in any way. As this area in white sharks is undiscovered none of these questions are known or proven. However it is known that sharks use long term memory in transoceanic migrations [R Bonfil et al, 2005], suggesting that many areas or landmarks can be stored and accessed at will. As this ecosystem is small it is logical to keep a small amount of patches where successful predations have occurred and for the purposes of this experiment a shark agent can store **four** previous predations.

The shark agent does however maintain the ability to store new predations as replacements of old ones, to avoid repeat visits to an area where a previous predation has occurred but isn't frequented by seals. With this method the shark agent is optimizing its set of stored previous predations by replacing its stored areas with new predations, so when visiting an area frequented by seals more predations will occur and more previous predations will be stored in a successful area, meaning the shark will frequent this area more. It is suggested that the white shark has a large capacity to hold long term memory but in this instance the shark is merely holding the four most recent previous predations to avoid having a static set of predations areas and whether this optimises the hunting strategy remains to be concluded.

The last issue that remains for discussion is the shark agent's selection of area to return to out of a possible four that it stores in memory. It is not logical to assume that the shark chooses a random area to return to, as the white shark is seen to be highly selective in other areas of its attack strategy such as prey selection when given a choice of unknown and familiar prey [A P Klimley et al, 1989). The optimal strategy would be to choose the closest of the four areas, as all four have an equal promise of predation success. If an algorithm were to be developed to order the areas of predation in relation to their distance to one another and thus determining which previous predation is in the optimal areas with regards to the other previous predations, then this would be the optimal way of prioritising each area. As there are only four areas being stored in this simulation this is irrelevant and perhaps an area for further study. Therefore the strategy of choice is to find the closest previous predation to the sharks point when choosing an area to revisit. The shark now has a four area list with an order in which to visit them until it finds prey.

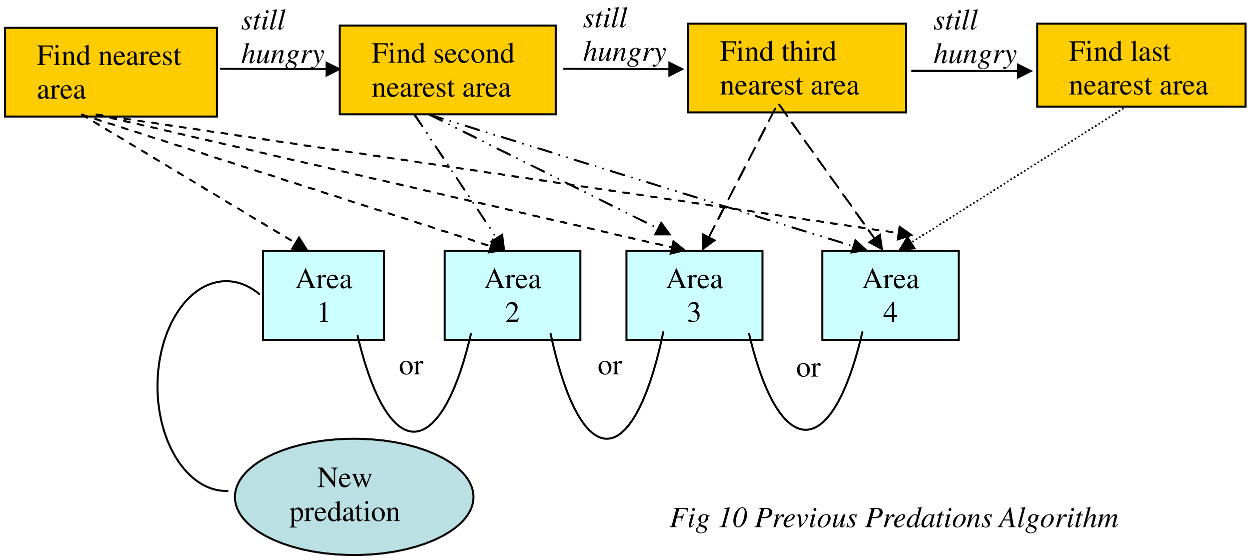
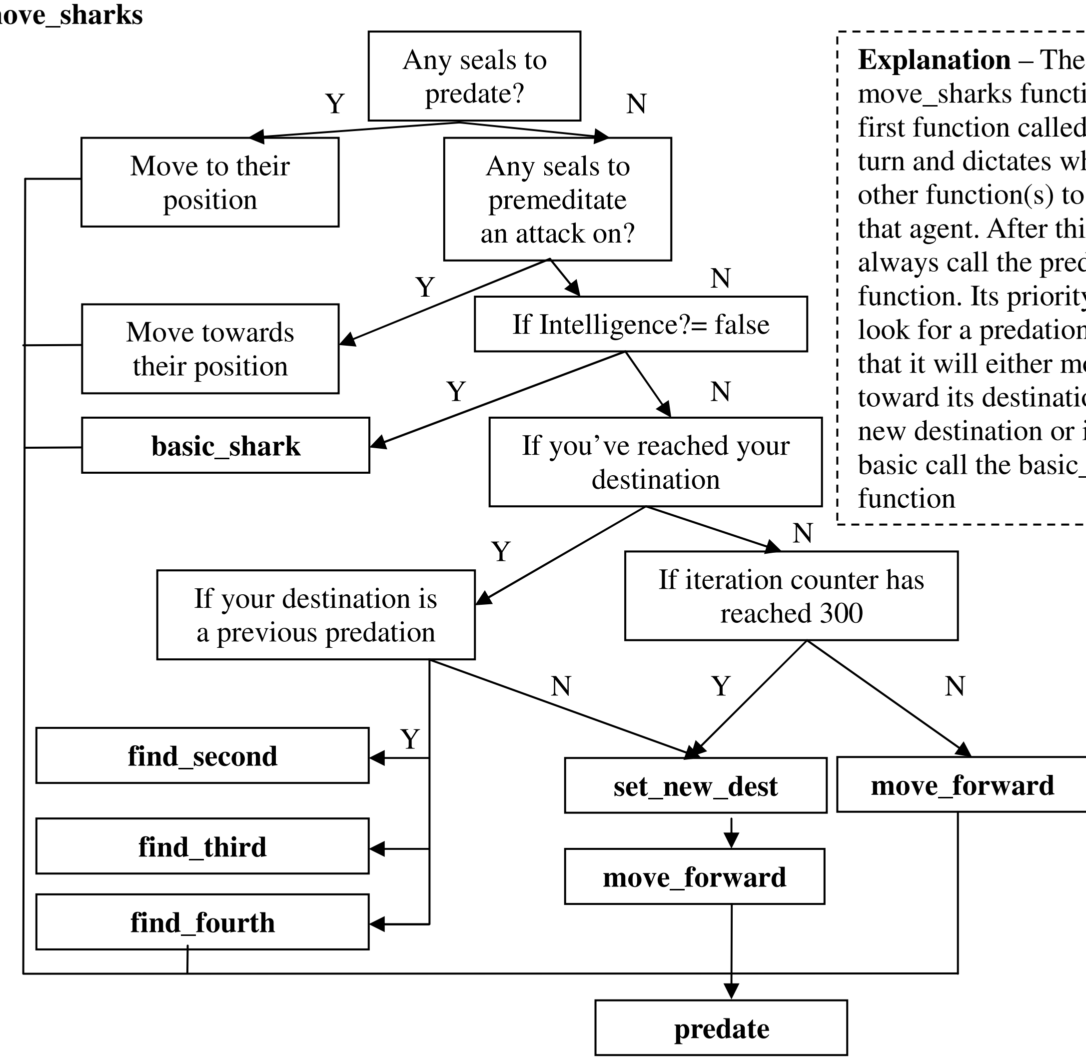


Fig 10 Previous Predations Algorithm

8.09 Shark Movement Decision Trees

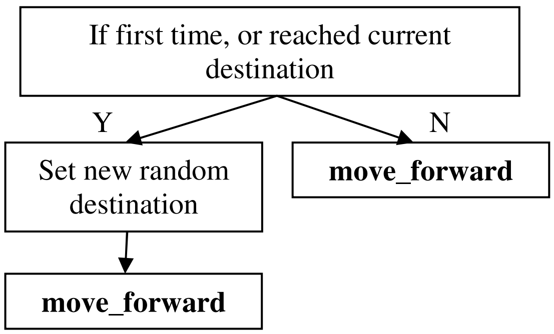
The following are decision trees based on the functions that make up the movement algorithm described in this chapter. Each decision tree represents one function; the best way of displaying such functions is through listing the functions. Unlike the seal movement each function cannot be thought of as a module as each function cannot be run independently as they are inter-dependant and have embedded calling of multiple functions within one another. With the previously listed description of the important variables and how the storage and choice of previous predation works within the shark agent behaviour the remaining behaviour should be understandable from the decision trees. All variables previously reference are capitalised and all functions are in bold.

move_sharks



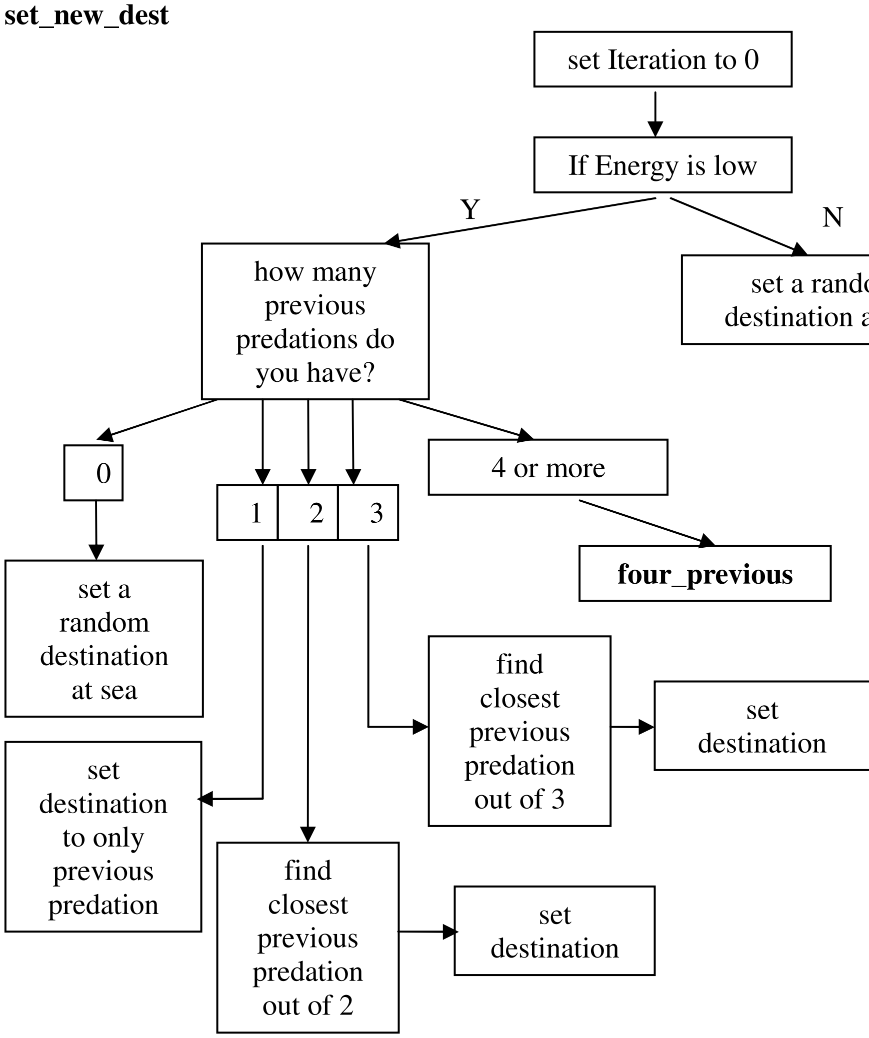
Explanation – The move_sharks function is the first function called each turn and dictates which other function(s) to call for that agent. After this it will always call the predate function. Its priority is to look for a predation, failing that it will either move toward its destination, set a new destination or if it's basic call the basic_shark function

basic_shark



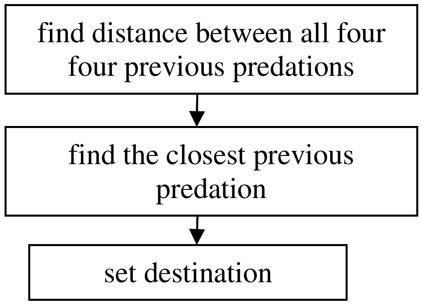
Explanation – The basic_shark function is very simple and it is the only function called when the Intelligence? variable is false. It simply asks the shark agent if it has a new destination or has reached its current one. If so it sets a random new one at sea and calls **move_forward**, otherwise it just calls **move_forward**.

set_new_dest



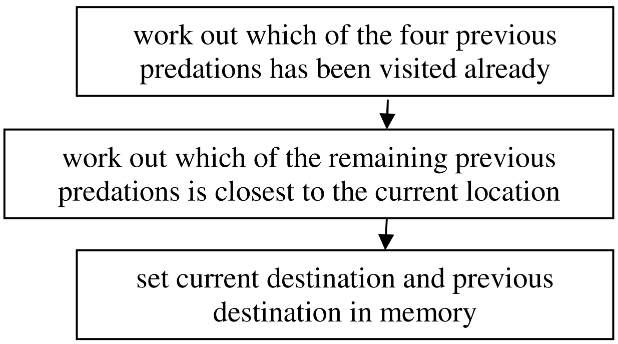
Explanation – Set new destination is the function called when a shark agent reaches its current destination and needs to set a new one. It has to decide whether the Energy is low enough to set a previous predation or a random new destination. If so it can find the closest previous predation. This is only called when an agent has reached a destination that isn't a previous predation.

four_previous



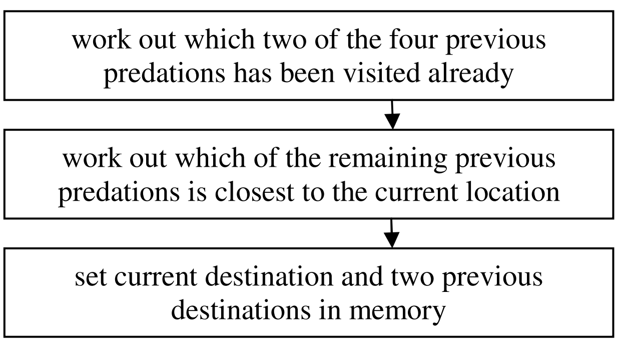
Explanation – Four previous is really a sub function of set_new_dest as it is only called by this function. It looks at all four previous predations and finds which is the closest by comparing to each other individually. Once it has found the closest it sets this as the shark agent's new destination.

find_second



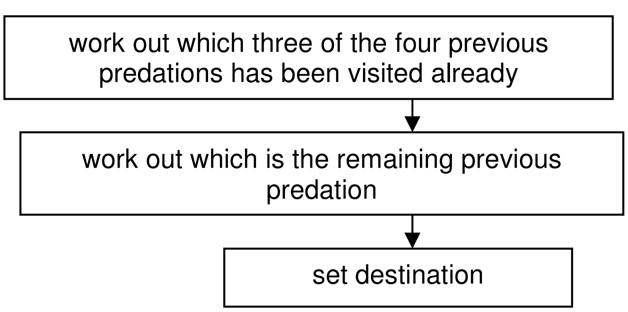
Explanation – Find second works by checking to see if which previous predation has been visited, then for each of these it finds the closest remaining previous predation and sets this as its new destination. This is called if the agent has visited one previous predation in a row and still has low energy.

find_third



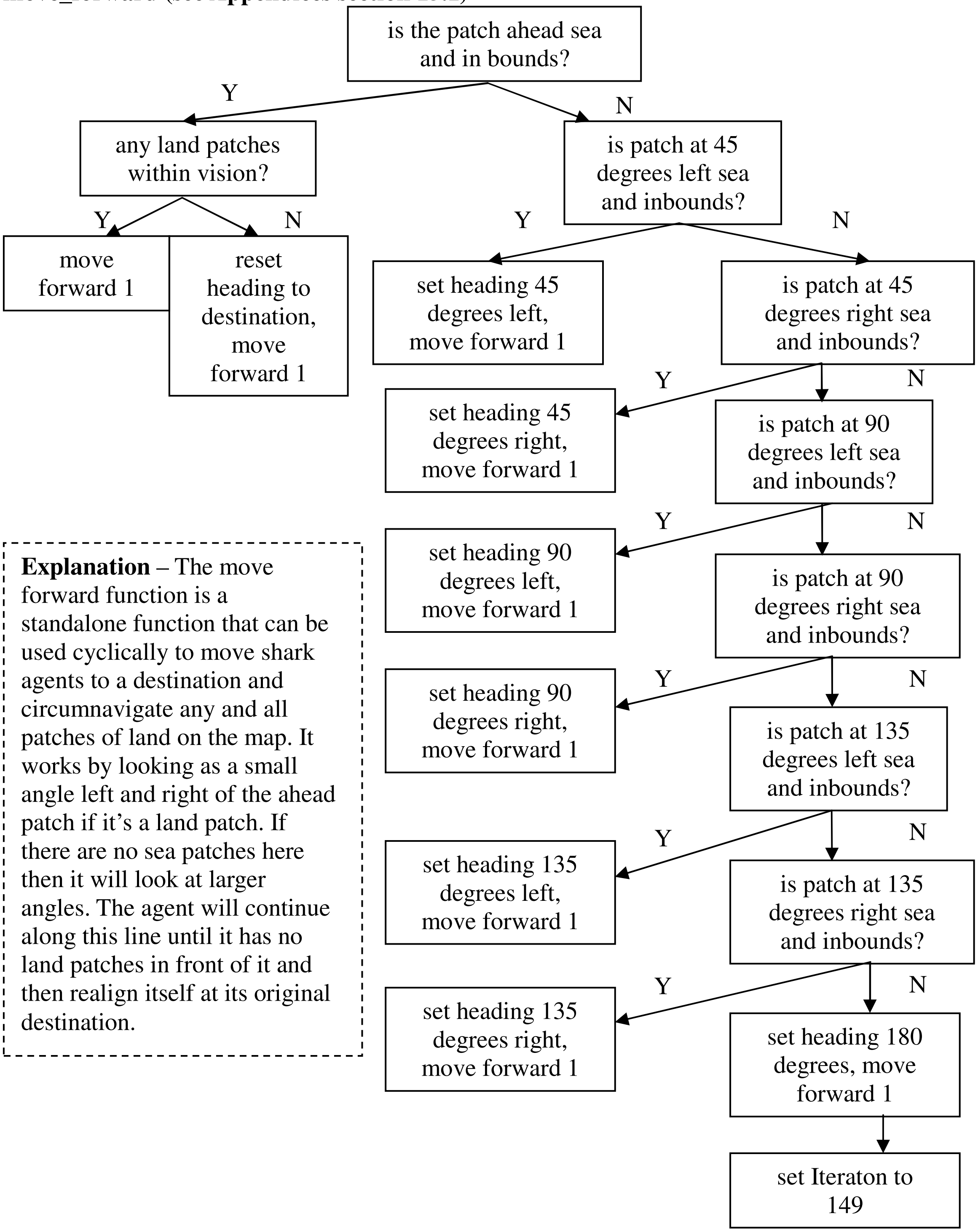
Explanation – Find third looks at all possible combinations of two previous predations that could have been previously visited, then for each of these finds the shortest distance to the remaining two and sets this as the next destination. This is called if the agent has visited two previous predations in a row and still has low energy.

find_fourth



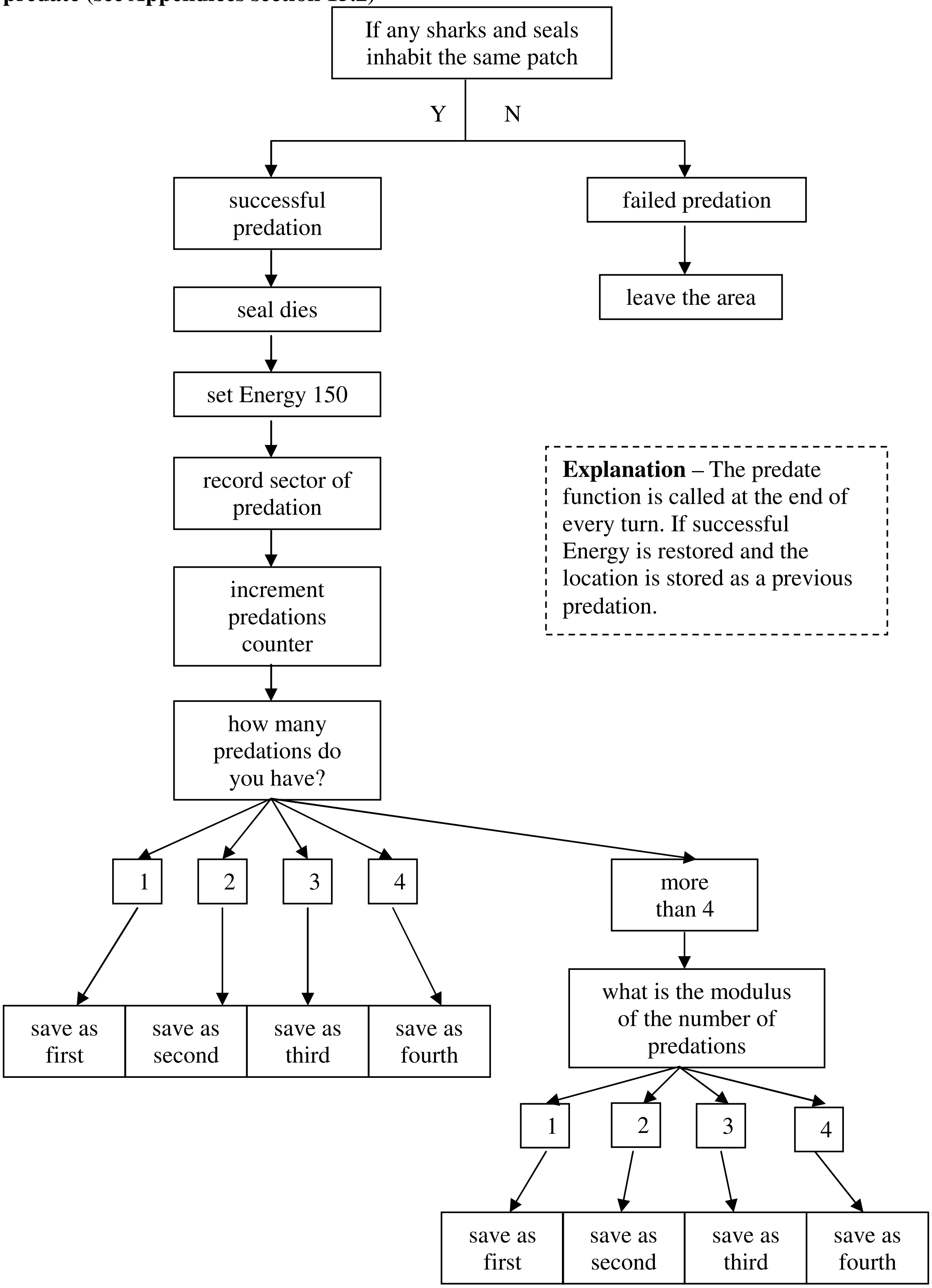
Explanation – Find fourth works by looking through all the possible combinations of previous predations as the last 3 destinations visited, when the correct one is found it sets the new destination as the fourth previous predation that hasn't yet been visited. This is called if the agent has visited three previous predations in a row and still has low energy.

move_forward (see Appendices section 15.1)



Explanation – The move forward function is a standalone function that can be used cyclically to move shark agents to a destination and circumnavigate any and all patches of land on the map. It works by looking as a small angle left and right of the ahead patch if it's a land patch. If there are no sea patches here then it will look at larger angles. The agent will continue along this line until it has no land patches in front of it and then realign itself at its original destination.

predate (see Appendices section 15.2)



Explanation – The predate function is called at the end of every turn. If successful Energy is restored and the location is stored as a previous predation.

8.10 Summary

To summarise the development phase thus far, firstly the non-functional and functional requirements of the ABM simulation were defined to produce a simulation that satisfies the fundamental requirement; **Provide an accurate simulation of Cape fur seals and white sharks in the Seal Island ecosystem, where white sharks predate seals and each predation occurs in a defined sector (1-6).**

Then the implementation phase began by firstly looked at the transition from a real ecosystem at Seal Island to a virtual environment in NetLogo was considered where various areas of seal and shark behaviour were defined as included or excluded due to their relevance of this simulation based on their necessity or effect on predation. Areas such as grouping, frolicking and remaining stationary were included in seal behaviour whereas specific evasive techniques such as mobbing and vigilance were deemed unnecessary for the scale of the simulation. Shark behaviour was defined as either basic or intelligent where basic behaviour was a random choice of destination of sea, whereas intelligence was simply an extension of this with successful previous predations stored as memory as an option to return once a destination had been reached.

Following this the constants and variables of the environment with supporting literature for each fixed constant where appropriate. The variables to be examined are defined as; the shark's choice of previous area of predation to return to (later defined in Fig 10 Previous Predations Algorithm), how the energy level of the shark effects its decision to travel to previous predations, the probability of the seal groups choosing which direction to travel away from the island and the ratio of shark agents to seal agents in the simulation to create an accurate representation of the real world numbers.

From these definitions, the two agents of the simulation needed their behaviour to be defined. This is done through the shark and seal agent behavioural models. The seal agent behavioural model is defined as hierarchy of modules (Fig 9) which each seal agent will work through, where the state of the seal agent is transient from each turn (or tick) and effects which modules are called. Each module was then described as a decision tree.

Similarly the shark agent behavioural model was defined by firstly determining the algorithm the shark uses to decide whether to go travel to a previous predation, and if so which of the four that it can hold does it travel to. It was defined as the closest to its current position as long this has not already been visited since the last predation (Fig 10). The rest of the shark behaviour model is described using decision trees for each function, showing how variables effect the decisions of each turn rather than states. From this implementation a working ABM simulation is produced that meets the fundamental non-functional requirement; **Provide an accurate simulation of Cape fur seals and white sharks in the Seal Island ecosystem, where white sharks predate seals and each predation occurs in a defined sector (1-6)**. With this in mind, the simulation now needs to be black-box and white-box tested to determine exactly if all functional and non-functional requirements are met as predicted therefore whether results generated are accurate and validate whether the experiment phase can begin.

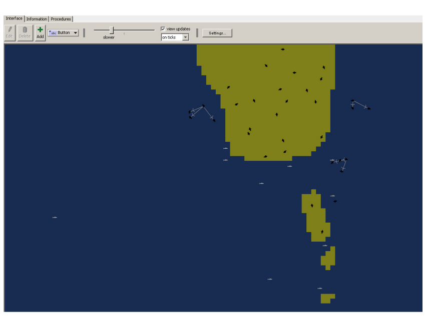


Fig 11 – SealsAndSharks.nlogo screen shot

9. Testing

Most white-box testing is carried out on a module basis, meaning every module is individually tested and then cross tested with any other working modules that it interacts with. There is pre-module testing of fixed functions and post-module testing of functions, this is done to check the functionality of the environment and of the user interactions that are relevant before and after the simulation is started. Colors were often used as a source of verification that the agent is running the intended code or performing the intended action as well as printed test messages and observation. The majority of the testing is white-box as the focus of the simulation is performance at experimentation phase rather than usability and as there are a limited number of potential users there is a smaller amount black-box testing required than white-box. All performance bugs are recorded and the solutions noted.

9.1 Pre-Module Testing; Functional Testing

Test F1: Testing that the Seal Island environment is loaded into NetLogo without glitches or irregular colours
Expected: The environment from Fig 5 will load into the NetLogo patch matrix with the colours interpreted into NetLogo colours to the nearest probable colour to those in Fig 5.
Result: Some differing irregular colours were interpreted by NetLogo, these need to be all the same for each section of the environment. A new function to turn irregular colours into white squares is written to overcome this as well as a function to then turn white patches into the modal (most frequent) colour of the eight neighbouring patches.
Condoned Pass

Test F2: Testing that the patches of sea and land are assigned an appropriate land or sea variable (land = 1 sea = 0 for land patches, sea = 1 land = 0 for all sea patches).
Expected: Patches with land assignments will turn beige then white (repeating) and all sea patches will remain blue.
Result: Some patches did not contain a modal neighbouring patch (equal 4 and 4 land and sea sector) in which case one was randomly chosen from the two candidates. This still left very few remaining white squares which could not be determined which sector of sea they were in and assigned as "border" patches"
Condoned Pass

Test F3: Testing that the sectors of the sea patches are assigned an appropriate sea sector variable (Sector = 1 - 6 for sectors 1 to 6).
Expected: As all the patches within the sector boundaries are already defined with their own colour, a test is run to invert all the colours of the separate sectors one at a time so each are confirmed as the correct sector.
Result: Expected
Passed

Test F4: Testing that all sea patches turn one colour (dark blue) and all land patches are one colour (beige) after the tests F1-3 complete.
Expected: Once the jpeg is loaded into NetLogo, irregular colours and white patches are correctly converted and all patches correctly assigned variables, all sea patches should turn dark blue whilst all land patches are beige. This should mean that there are only two different colours in the environment creating better esthetics and giving a clearer distinction to the user between sea and land.
Result: Expected
Passed

9.2 Seal Movement Module Testing

Module 1: move_seals
Test 1.1: Testing the random assignment of functions to neutral state seals.
Expected: Seals assigned do_nothing turn yellow (20/25), Seals assigned lets_frolic turn green. (1/25), Seals assigned form_group turn pink. Flashing seal colors with majority yellow, some green and minor amounts of pink.
Result: Expected
Passed

Test 1.2: Testing the random assignment of functions to neutral hidden state seals.
Expected: Hidden seals assigned do_nothing turn their patch square yellow (4/5), seals assigned travel_back turn their patch square blue (1/5).
Result: Expected
Passed

Test 1.3: Testing state 1
Expected: All seals should turn blue when after being assigned state 1 (travel back) then tested.
Result: Expected
Passed

Test 1.4: Testing state 2
Expected: All seals should turn blue when after being assigned state 2 (frolic) then tested.
Result: Expected
Passed

Test 1.5: Testing state 3
Expected: All seals should turn blue when after being assigned state 3 (form group) then tested.
Result: Expected
Passed

Test 1.6: Testing state 4
Expected: All seals should turn blue when after being assigned state 4 (travel away) then tested.
Result: Expected
Passed
Module Passed

Module 2: do_nothing
Test 2.1: Testing the wait function
Expected: Making sure seal agents stay static for the given wait period by moving the seal after the function is called. All seals should move forward after 20 seconds of wait and then repeat.
Result: Expected
Passed
Module Passed

NB: For a list of all White-Box testing on seal movement modules see section 17.1

9.3 Shark Movement Module Testing

Module 1: move_sharks

Test 1.1: Testing that sharks agents recognise seal ages within its close-range vision ready for predation
Expected: Sharks should recognize seal agents within the two patch 270 degree cone radius which will then turn the seal within this range red. In most cases a failure message will be printed while some will be close enough to turn all seals within this vision red.
Result: Expected
Passed

Test 1.2: Testing that sharks agents recognise seal ages within its vision so it start premeditating an attack
Expected: Sharks should recognize seal agents within the four patch 270 degree cone radius which will then turn the seal within this range blue. In most cases a failure message will be printed while some will be close enough to turn all seals within this cone-vision blue.
Result: Expected
Passed

Test 1.3: Testing that sharks agents recognize seal ages firstly within its close-range vision and secondly within its full vision.
Expected: Sharks should recognise seal agents within the two patch 270 degree cone radius which will then turn the seal within this range red then any seals within the four patch radius but not close enough to be in the two patch radius will turn blue. In most cases a failure message will be printed while most of the seals will be blue and some red.
Result: Expected
Passed

Test 1.4: Check that after Test 1.3 is completed the ‘Intelligence?’ variable is successfully verified as negative or positive depending on the user’s switch.
Expected: Test 1.3 should complete as expected then all seals should turn green if ‘Intelligence?’ is ‘off’ (false) or pink if switched to ‘on’ (true).
Result: Expected
Passed

Test 1.5: Test that a new destination is set under all the correct conditions to set a new destination and move to their intended destination.
Expected: Conditions when a new destination should be set are as follows; there is no initial destination set, the agents has reached its current destination with no p-iterations or the move-iteration counter has reach 300 (a get-out clause for infinite movement loops). A white patch should be highlighted when each of these three conditions are met separately (indicated by a printed message) and then turn black once reached.
Result: Expected
Passed

Test 1.6: Testing that the move_sharks module behaves exactly as it should.
Expected: Tests 1.1-6 should repeat cyclically with the expected results.
Result: Expected
Passed
Module Passed

NB: For a list of all White-Box testing on shark movement modules see section 17.2

9.4 Shark and Seal Agent Coherence Test

Inter-Module Testing: All shark movement modules and All seal movement modules

Test M11: Testing that the seal and shark agent's behaviour work together as expected, predations occur and that the simulation meets the requirements set out.

Expected: As expected from Test M8 from the shark behaviour module testing and Test M4 from the seal movement module testing. Agents should predate each other and not become trapped in any infinite loops, the simulation should halt when all seals are predated.

Result: As expected with occasional anomalies where between one and three seals, when becoming the last surviving seals of the species, will become hidden and not return to land. This is due to their root (or leader) seal being predated). This can be overlooked as there is no real reason why all seals have to be predated. At this point the simulation can be manually halted and the missing seals attributed to leaving the island permanently.

Condoned Passed

All agent based movement and behaviour passed

9.5 Post-Module Testing; Functional Testing

Test F5: Testing that all predations are counted and displayed in the user panel and all counts of predations in each sector 1-6 are displayed.

Expected: The displays in the user panel should show a changing count whilst the simulation is running and give a fixed number within the correct range of predations when the simulation halts.

Result: Expected

Passed

Test F6: Testing that the seal agent number slider and shark agent number slider alter the number of seal and shark agents in the simulation before the simulation is run.

Expected: The seal and shark agent numbers should correspond to those displayed on the sliders in the user panel.

Result: Expected

Passed

Test F7: Testing that the setup button loads the environment and agents and that the go button performs the simulation as expected in Test M11.

Expected: When the intelligence switch is off, this should perform as expected in M11 with 'Intelligence?' is false, when switched on it should perform as expected when 'Intelligence?' is true.

Result: Expected

All White-Box Tests Passed

9.6 Black-Box Testing

All tests carried out in this section are done under the pretence that the user knows nothing of the code and has a little working knowledge of the user interface in NetLogo 4.0.4, if the user does not meet these requirements then it is suggested to read the following website; http://ccl.northwestern.edu/netlogo/docs/ Each test is carried out on 5 subjects that meet these prerequisites.

Test 1: Test that the user can open the simulation SharksAndSeals.nlogo
Prerequisites: A working running version of NetLogo 4.0.4, a known saved location of the files SharksAndSeals.nlogo and seal_island_no_outline.bmp
Procedure: User clicks 'File' then 'Open' from the menu bar. Then the user browses to the location of the file SharksAndSeals.nlogo and clicks 'Open'. The user then navigates to the 'Procedures' tab and checks the line import-pcolors "C:\\seal island no outline.bmp", if this file is not at the specified location then this has to be altered accordingly. The file is now opened.
Results: 5 out of 5 complete.
Passed

Test 2: Test that the simulation can be setup and run by all users.
Prerequisites: An open simulation of SharksAndSeals.nlogo in NetLogo 4.0.4
Procedure: User clicks 'Setup' and then waits for environment to load, then the user clicks 'Go'. The simulation should then run and finish.
Results: 4 out of 5 complete, a fairly long wait for the environment to load due to NetLogo loading in the jpeg file. Consequently one user does not complete the running of the simulation. Nothing can be done to change this load time as it is due to the jpeg file which cannot be altered.
Condoned Pass

Test 3: Test that the simulation can be setup and run by all users with user changeable variables.
Prerequisites: An open simulation of SharksAndSeals.nlogo in NetLogo 4.0.4
Procedure: User alters the shark agent number slider, the seal agent number slider and the intelligence switch. User clicks 'Setup', then waits for environment to load with the appropriate changed variables, then user clicks 'Go'. The simulation should then run and finish.
Results: 5 out of 5 complete.
Passed

Test 4: Test that the information is shown and recognised by all users
Prerequisites: A version of SharksAndSeals.nlogo has been run and completed.
Procedure: Information is displayed in the counter boxes in the user panel. User looks and interprets the information displayed in the counter boxes in the user panel when the simulation has halted.
Results: 3 out of 5 complete, one did not understand the significance of the numbers in any of the boxes whilst another did not understand the significance of the numbers in the 'Sector' boxes. Consequently more information and help has been written in the 'Information' tab of the simulation.
Condoned Pass

Test 5: Test that the information about the simulation can be viewed by all users
Prerequisites: An open simulation of SharksAndSeals.nlogo in NetLogo 4.0.4
Procedure: User clicks the Information tab which displays all the relevant information
Results: 5 out of 5 complete.
Passed

Part III
Results

10. Hypotheses

Hypothesis (1); White sharks can premeditate their attacks on Cape fur seals.

Looking at the methods of known white shark hunting techniques it's obvious that their array of sensory methods of detection such as the lateral line [J Mogdans et al, 2001][J Engelmann et al, 2000], olfaction [A Miklósi et al, 1989], and chemoreception as well as intelligence in choice and strategy [R S Collier et al, 1996]. The idea that white sharks use memory to aid their premeditation of prey is feasible from what is known about the memory of fish [V Csányi et al, 1989] and fish cognition [C Brown et al, 2006]. Premeditation can be interpreted in numerous ways, for the following experiments premeditation is defined as remembering areas of successful previous predation and returning to the areas selectively as a means of optimising predation success. Furthermore the new hypothesis derived from the original with the definition of premeditation defined and with the context being explicitly defined as Seal Island.

Hypothesis (2); when predating Cape fur seals, white sharks can selectively return to areas of previous successful predation to optimise the chance of successive predation in the ecosystem of Seal Island with defined sectors of surrounding water.

This definition can still be refined further to accommodate the specific rules of the shark and seal agents and the boundaries of the simulation. As shark agents in this simulation can hold four different specific areas of predation and use a stack structure to hold the current previous predations and pop off old ones to add new ones, this behaviour has to be defined as does the grouping behaviour of the seals. The context of the specific simulation and the interpretation of the environment from the Seal Island ecosystem should also be included in the new hypothesis.

Hypothesis (3); when predating Cape fur seal agents in a NetLogo simulation, white shark agents can store four previous areas where successful predation has occurred, where one is replaced as a new successful predation occurs. The shark agents select to a return to these areas to optimise the chances successive predation. Seal agents exhibit an accurate grouping and behavioural reflection of Cape fur seal behaviour within the boundaries and scope of the experiment. The environment is modelled on Seal Island where six sectors of sea area are defined.

The final hypothesis makes specific reference to the results looking to be obtained when comparisons are made to Martin's observations.

Hypothesis (4); when predating Cape fur seal agents in a NetLogo simulation, white shark agents can store four previous areas where successful predation has occurred, where one is replaced as a new successful predation occurs. The shark agents select to a return to these areas to optimise the chances successive predation. Seal agents exhibit an accurate grouping and behavioural reflection of Cape fur seal behaviour within the boundaries and scope of the experiment. The environment is modelled on Seal Island [R A Martin et al, 2005] where six sectors of sea area are defined. The occurring predations will show positive correlation to Martin's records of observed shark predations in comparison to shark agents without the programmed intelligence as evidence of Hypothesis 1 and 2.

11. Experimentation

The experimentation phase is designed to alter variables in the simulation and record the results that occur to find the best results in relation to the control. The results will then be listed and all conclusions from these will be properly drawn up and explained in section 12. There are nine experiments that will take place and each one highlights a particular variable where a separate conclusion can be drawn. There are three variables that can be changed, the ratio of seals to sharks, the intelligence algorithm and the probability of seal groups choosing which direction to head. By changing these one at a time there are eight permutations to create and a final ninth experiment aiming to recreate as much accuracy to reality as possible. From these experiments enough conclusions can be drawn from the results to signify the relevance between the intelligence algorithm and the real life findings.

11.01 Experimental Constraints and Variables

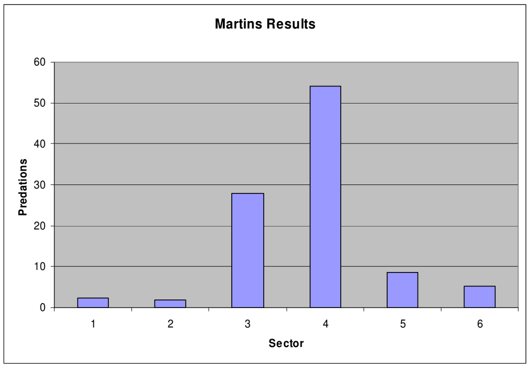
The simulation is run under a time constraint, something that has been created for the purpose of these experiments rather than anything representative of the real world. This constraint is to stop the simulation from being caught in an infinite loop. As each simulation will not always result in 100% of the seal agents being predated, this ensures the results are processed and the simulation stops. The simulation will calculate the percentage of predations for each sector and output this as a result rather than the exact number of predations; this is so that each set of results is directly comparable with the control which is a percentage result. With this constraint there is also an allowance for comparison for hunting efficiency between the basic and intelligent sharks by the average final number or predated seals for each agent type within the fixed limit.

The simulation is run with a fixed number of agent and seal sharks, as it is implausible to have an accurate representation of real world numbers of seal agents the ratio of shark agents to seal agents has to be representative. As the exact number of predations is not the variable under examination and results are being processed as percentage representations also, there is no detriment to the validity of the results as long as the ratio is accurate. There are clearly less sharks than seals populating Seal Island and as the seal population is known to be an average of 64,000 [R A Martin et al, 2005] and the highest recorded number of white sharks at Sea Island is 26 [R A Martin et al, 2005] taking an exact sample size in with a ratio of 64,000 to 26 would result in 2461 to 1. This large amount of seal agents would cause the simulation to run slowly and prevent quantitative testing, so in order to maintain some form of consistency two ratios will be used per experiment. The first is a relatively low ratio of 5:1 (100 seals to 20 shark agents) and 100:1 (100 seals to1 shark agent), with the latter being the more accurate set due to the greater accuracy to real life.

The decision for a seal leader to choose a direction to head away from the island is bias but the exact probability is unknown. Martin describes it as "Most movement… between sectors 3 and 4, significantly more at 4 than 3." So there will be two alternatives experimented with Sector 4 (6/8), Sector 3 (1/8), any random sector (1/8) and Sector 4 (4/8), Sector 3 (2/8), any random sector (2/8). Due to the high element of randomness (the starting position of the agents, the seal behavioural decisions and group direction heading decisions) in the coding of the behaviour of both shark and seal agents, each experiment will have 20 executions of simulation where the results are automatically outputted, then stored in a table and the averages calculated. The results shown here will be the averages of the results calculated. A visual representation of the results will be given with a bar chart as well as having the actual results printed for easy comparison. The results for each experiment will be commented on and concluded in the following section. Any percentage of predation not compensated for by a sector is not listed as it is a border predation occurring on a patch bordering two sectors or bordering land and sea.

11.02 Control Test

Title: Recorded results of the number of predations occurring in the sectors of Seal Island out of 2088 predations observed over a 6 year period.
Aim: To have a control test as a basis of comparison for all other experiments.
Method: Results taken from the paper "Predatory Behaviour of White Sharks at Seal Island, South Africa. R A Martin, N Hammerschlag, R S Collier, C Fallows, 2005."
Results:



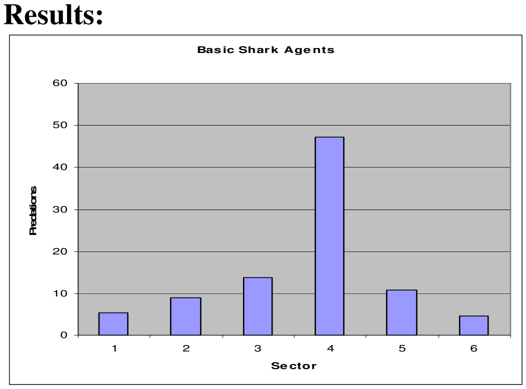
Sector 1	=	**2.3** %
Sector 2	=	**1.9** %
Sector 3	=	**27.8** %
Sector 4	=	**54.1** %
Sector 5	=	**8.6** %
Sector 6	=	**5.3** %
Predations	=	2088

Fig 12 Control Test Results

Analysis: These percentages presented are the ideal target for the intelligent experiments. The bar chart presents a broader view of comparison for each experiment although any significant findings will be used in a bar chart with these results for direct comparison.

11.03 Experiment 1

Title: Results obtained using the simulation SharksAndSeals.nlogo by replicating the variables described below, executing the simulation 20 times then taking the average from the outputted results.
Aim: To find if the set variables represent a value close to the control test and to subsequent tests.
Variables: Intelligence? = false, **Shark to Seal Ratio** 20:100, **Seal Group Behaviour** (6/8, 1/8, 1/8)
Method: The correct variables are set using the user panel and by altering the probability statements dependant on random numbers within the code.
Results:



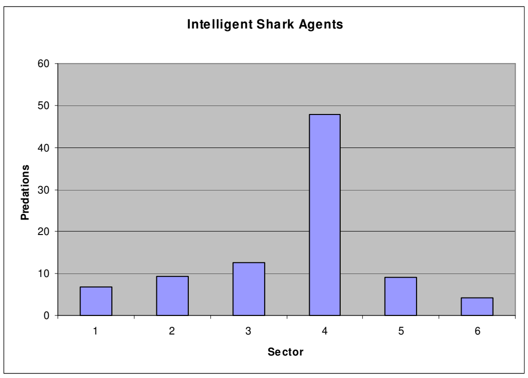
Sector 1	=	5.45 % av
Sector 2	=	9.05 % av
Sector 3	=	13.7 % av
Sector 4	=	47.2 % av
Sector 5	=	10.85 % av
Sector 6	=	4.6 % av
Predations	=	94.95 av

Fig 13 Experiment 1 Results

Analysis: The results show good correlation to the Control Test with slightly more spread over the total sectors and significantly less in sector 3. This indicates that the seal agents are moving and populating the areas of the sea, it does not give much indication of the shark agent movement until there are further experiments for comparison.

11.04 Experiment 2

Title: Results obtained using the simulation SharksAndSeals.nlogo by replicating the variables described below, executing the simulation 20 times then taking the average from the outputted results.
Aim: To find if this experiment differs from Experiment 1, variable changed = **Intelligence?**.
Variables: Intelligence? = true, **Shark to Seal Ratio** 20:100, **Seal Group Behaviour (**6/8, 1/8, 1/8)
Method: The correct variables are set using the user panel and by altering the probability statements dependant on random numbers within the code.
Results:



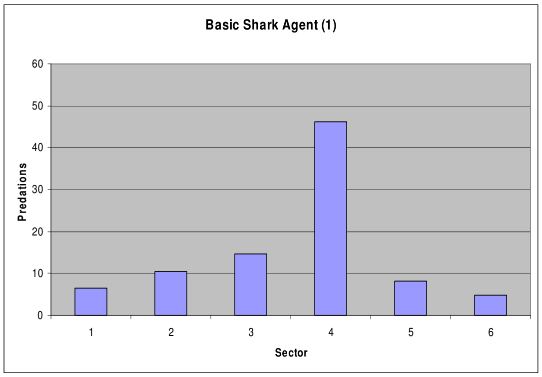
Sector 1	=	6.7 % av
Sector 2	=	9.4 % av
Sector 3	=	12.65 % av
Sector 4	=	47.75 % av
Sector 5	=	9.2 % av
Sector 6	=	4.1 % av
Predations	=	94.95 av

Fig 14 Experiment 2 Results

Analysis: The results are almost identical to Experiment 1, with very small margins of change in all sectors. This suggests that one or more of the other variables are incorrect as the shark behaviour from these two results suggests no difference. The most likely reason for these almost identical results is the large amount of sharks causing over-predation and thus the results shown are just a representation of the seal population. Therefore reducing the number of sharks to seals should show better results. If this is the case then it can also be determined that

11.05 Experiment 3

Title: Results obtained using the simulation SharksAndSeals.nlogo by replicating the variables described below, executing the simulation 20 times then taking the average from the outputted results.
Aim: To find if the shark ratio 1:100 has an effect on the success of predation and the sectors it occurs.
Variables: Intelligence? = false, **Shark to Seal Ratio** 1:100, **Seal Group Behaviour (**6/8, 1/8, 1/8)
Method: The correct variables are set using the user panel and by altering the probability statements dependant on random numbers within the code.
Results:



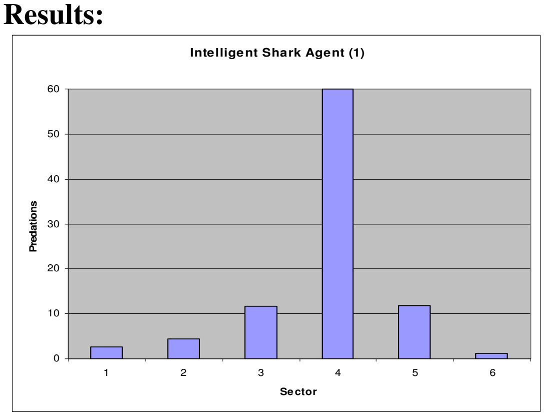
Sector 1	=	6.55 % av
Sector 2	=	10.45 % av
Sector 3	=	14.7 % av
Sector 4	=	46.2 % av
Sector 5	=	8.25 % av
Sector 6	=	4.8 % av
Predations	=	28.85 av

Fig 15 Experiment 3 Results

Analysis: This is the first experiment to exhibit significant difference from the other experiments. The spread of the results shows little correlation to the Control Test and significantly higher results in the sector 4 in relation to sector 3, suggesting that the seal movement probability is too weighted towards sector 4 with no enough weight on sector 3.

11.06 Experiment 4

Title: Results obtained using the simulation SharksAndSeals.nlogo by replicating the variables described below, executing the simulation 20 times then taking the average from the outputted results.
Aim: To find if the results correlate to the Control Test in comparison to Experiment 3. Variable changed = **Intelligence?**.
Variables: Intelligence? = true, **Shark to Seal Ratio** 1:100, **Seal Group Behaviour** (6/8, 1/8, 1/8)
Method: The correct variables are set using the user panel and by altering the probability statements dependant on random numbers within the code.
Results:



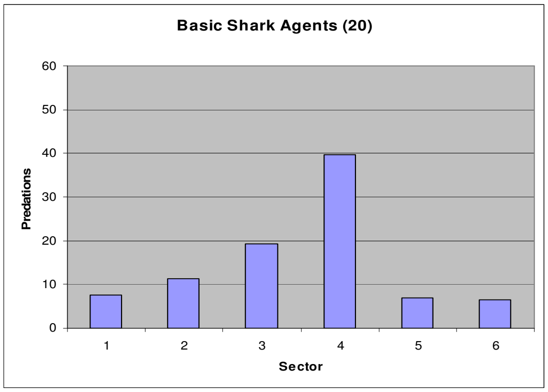
Sector 1	=	2.7 % av
Sector 2	=	4.4 % av
Sector 3	=	11.6 % av
Sector 4	=	59.9 % av
Sector 5	=	11.75% av
Sector 6	=	1.25% av
Predations	=	42.4 av

Fig 16 Experiment 4 Results

Analysis: In direct comparison to Experiment 3, there is now an obvious comparison to be made in relation to the movement of the shark agents. These results clearly show a higher predation count and a high concentration of predation in sector 4. This suggests two things, that the intelligent shark agents have a superior algorithm for optimising predation success and secondly that the seal population is definitely to bias toward sector 4. Therefore the next set of four experiments with the reduced seal agent probabilities should provide a more accurate set of results. There is positive correlation in sector 4, 5, 6, 1 and 2 to the Control Test however the sector 3 results should be higher and sector 4 slightly lower, this suggests that the intelligence algorithm relates closer to reality than the basic, and that the seal population is again too high in sector 4.

11.07 Experiment 5

Title: Results obtained using the simulation SharksAndSeals.nlogo by replicating the variables described below, executing the simulation 20 times then taking the average from the outputted results.
Aim: To find if the new seal group behaviour probabilities reflect more accurate correlation to Control.
Variables: Intelligence? = false, **Shark to Seal Ratio** 20:100, **Seal Group Behaviour** (4/8, 2/8, 2/8)
Method: The correct variables are set using the user panel and by altering the probability statements dependant on random numbers within the code.
Results:



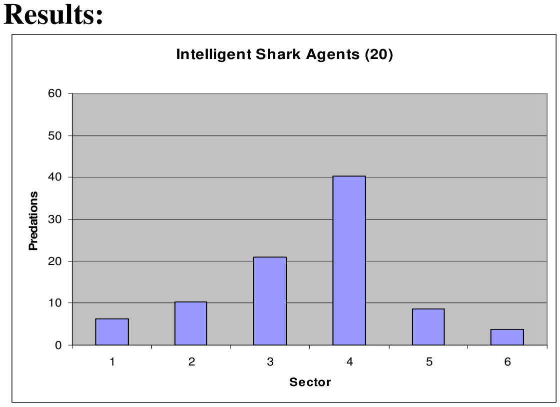
Sector 1	=	7.5
Sector 2	=	11.4% av
Sector 3	=	19.35% av
Sector 4	=	39.6% av
Sector 5	=	6.95% av
Sector 6	=	6.5% av
Predations	=	95.1 av

Fig 17 Experiment 5 Results

Analysis: There is a much more spread set of results in this case, suggesting that the difference in the seal group behaviour probabilities has taken an effect. It is difficult to predict how much of an impact the shark behaviour has had on the results as these results may be another example of too many shark agents for the amount of seal agents.

11.08 Experiment 6

Title: Results obtained using the simulation SharksAndSeals.nlogo by replicating the variables described below, executing the simulation 20 times then taking the average from the outputted results.
Aim: To find if the results correlate to the Control Test in comparison to Experiment 5. Variable changed = **Intelligence?**.
Variables: Intelligence? = true, **Shark to Seal Ratio** 20:100, **Seal Group Behaviour (**4/8, 2/8, 2/8)
Method: The correct variables are set using the user panel and by altering the probability statements dependant on random numbers within the code.
Results:



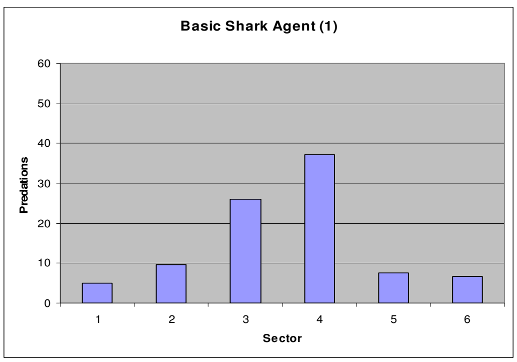
Sector 1	=	6.3 % av
Sector 2	=	10.3 % av
Sector 3	=	20.95 % av
Sector 4	=	40.2 % av
Sector 5	=	8.5 % av
Sector 6	=	3.8 % av
Predations	=	95.9 av

Fig 18 Experiment 6 Results

Analysis: In comparison to Experiment 5, these results shows a small amount of positive correlation to the Control Test, but similarly to Experiment 1 and Experiment 2 there is very little between the results to count as a significant contribution to the knowledge of the intelligent shark agents. It does however confirm that the larger ratio of sharks to seals (20:100) does not give significant results to represent the shark movement, and instead give a fairly accurate representation of the seal populations.

11.09 Experiment 7

Title: Results obtained using the simulation SharksAndSeals.nlogo by replicating the variables described below, executing the simulation 20 times then taking the average from the outputted results.
Aim: To find if the smaller ratio of sharks to seals creates closer correlation to Control in comparison to Experiments 5 and 6.
Variables: Intelligence? = false, **Shark to Seal Ratio** 1:100, **Seal Group Behaviour** (4/8, 2/8, 2/8)
Method: The correct variables are set using the user panel and by altering the probability statements dependant on random numbers within the code.
Results:



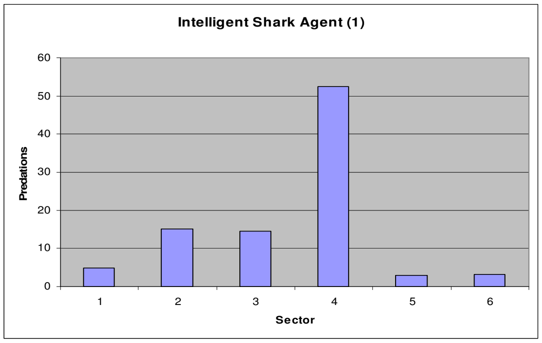
Sector 1	=	5 % av
Sector 2	=	9.6 % av
Sector 3	=	25.95 % av
Sector 4	=	37.1 % av
Sector 5	=	7.6 % av
Sector 6	=	6.7 % av
Predations	=	26.5 av

Fig 19 Experiment 7 Results

Analysis: The results are again for more significant with the 1:100 ratio, they show a low spread with a higher percentage in sector 3 as predicted. The predations in sector 4 are significantly lower than the control test.

11.10 Experiment 8

Title: Results obtained using the simulation SharksAndSeals.nlogo by replicating the variables described below, executing the simulation 20 times then taking the average from the outputted results.
Aim: To find if the results correlate to the Control Test in comparison to Experiment 7. Variable changed = **Intelligence?**.
Variables: Intelligence? = true, **Shark to Seal Ratio** 1:100, **Seal Group Behaviour** (4/8, 2/8, 2/8)
Method: The correct variables are set using the user panel and by altering the probability statements dependant on random numbers within the code.
Results:



Sector 1	=	4.85 % av
Sector 2	=	15.05 % av
Sector 3	=	14.4 % av
Sector 4	=	52.4 % av
Sector 5	=	2.85 % av
Sector 6	=	3.1 % av
Predations	=	37.7 av

Fig 20 Experiment 8 Results

Analysis: The results show positive correlation to the Control Test in comparison to Experiment 7 in sectors 4, 5, 6 and 1. Sectors 3 and 2 are too evenly spread. However the average predation number is again much higher, suggesting that the intelligence algorithm optimises successful predation. As Experiment 8 and 7 are the most significant with the variables defined as most accurate (1:100 ratio and probabilities (4/8) (2/8) (2/8)) they therefore hold the most merit when looking at the intelligence algorithm which is undoubtedly optimal in the success of predation.

11.11 Experiment 9

Title: Results obtained using the simulation SharksAndSeals.nlogo by replicating the variables described below, executing the simulation once then taking the direct result. Then changing the Intellgence? variable and repeating

Aim: To find if the set variables represent a value close to the control test and to subsequent tests.

Variables: Intelligence? = true and false, **Shark to Seal Ratio** 1:2461, **Seal Group Behaviour** (4/8, 2/8, 2/8)

Method: The correct variables are set using the user panel and by altering the probability statements dependant on random numbers within the code.

Results:

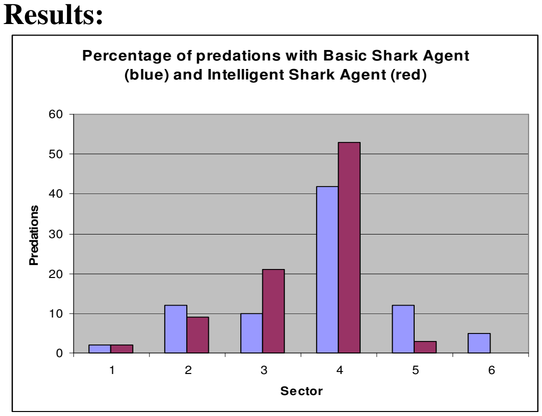


Fig 21 Experiment 9 Results

Sector 1	=	2 % av
Sector 1	=	2 % av
Sector 2	=	12 % av
Sector 2	=	9 % av
Sector 3	=	10 % av
Sector 3	=	21 % av
Sector 4	=	42 % av
Sector 4	=	53 % av
Sector 5	=	12 % av
Sector 5	=	3 % av
Sector 6	=	5 % av
Sector 6	=	0 % av

Analysis: These results show remarkable correlation in 4 sectors for the intelligent agents, sectors 4, 3, 2 and 1. Sector 5 and 6 are less signficant sectors and this therefore is strong suggestive evidence that the intelligent shark agents show similar results that that or real sharks supporting the defined hypotheses 4, 3 and 2. This is not conclusive as each test was only run once, however from the analysis of the results thus far the variables in this experiment have the most accurate values.

11.12 Comparison of Experiments 7, 8 and the Control Test

Results:

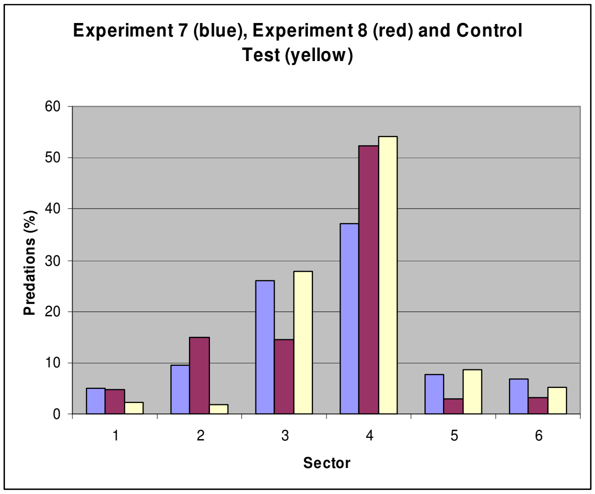


Fig 22 Experiment 7, Experiment 8 and Control Test Results

Analysis: From Fig 20 the yellow bars represent the control test, the red bars represent the intelligent sharks and the blue bars represent the basic. From closer inspection the red bars show closer correlation to the yellow in sector 4, 1 and 6 whereas the basic show closer correlation in 3, 2 and 5. The most significant result is in sector 4, the most significant sector. The margin between the blue and red bars here show how the intelligence algorithm optimises predation in the most populated area, as proven by the correlation to Martins findings of real world observation.

11.13 Comparison of Experiments 9 and the Control Test

Results:

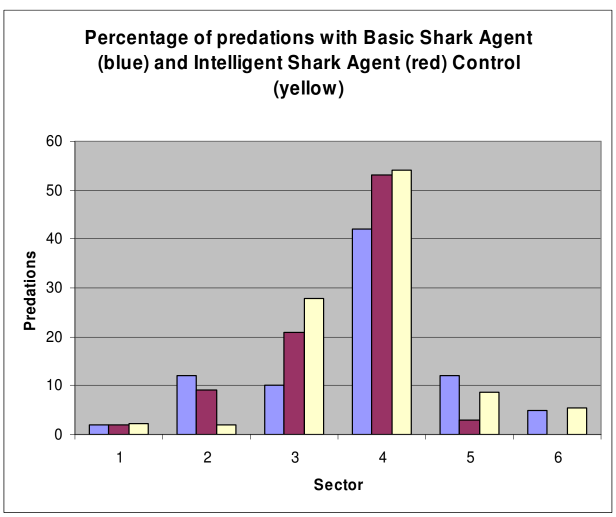


Fig 23 Experiment 9 and the Control Test Results

Analysis: All sectors except for the less significant sectors 5 and 6 show positive correlation to Martin's findings for the intelligent agents. This is solely the most significant evidence of positive correlation to the real findings of Martin supporting hypothesis 4, 3 and 2. The margin of difference in sector 4 (the most significant) is very small between Martin's findings and the intelligent agents which is further evidence of this.

12. Conclusions

In this section there are many comparisons and relationships to discuss and compare from the experiments undertaken in the previous section. Each relationship that is relevant for discussion will be compared with the underlying intention of finding positive correlation between the intelligence algorithm results and those of the control test. Other specific aspects of the results that have been observed or recorded in the accumulation table may also be touched on and referenced to the results tables in the appendices where appropriate.

12.1 The Relationship between the Ratio of Shark Agents to Seal Agents

Comparing the relationship between the experiments with 20:1 ratio and 100:1 ratio there seems to be a clear differentiation between the collective results as the 20:1 ratio would create very similar results with little differentiation between all experiments. An example of this is the comparison between Experiment 5 and 6 showing very little differences and similarly Experiment 1 or Experiment 2. When examining Experiments 7 and 8 you can see a much clearer correlation between the intelligent shark agent and the Control Test and the basic shark agent shows much more spread results and negative correlation to the control. This would support the idea that if the shark to seal ratio is too low and that over predation occurs giving only a representation of where the seal agents are populating rather than giving any representation of the shark agent's hunting strategy. This would also support the idea of positive correlation between intelligent shark agent's predations and the Control Test as the closer to the real life ratio of sharks and seals are. For this reason Experiment 9 was created to test this theory.

12.2 The Relevance of Experiment 9

From the findings of Experiments 7 and 8 the Experiment 9 test was contrived. It is designed to test the idea that the closer to reality the shark to seal ratio is the more positive correlation is shown in the intelligent shark agents and the more negative correlation is shown by the basic shark agents. Therefore a test was contrived with the exact ratio of 1:2461 sharks to seals as representative of the real ecosystem [R A Martin et al, 2005] however the method of testing was limited to only one test per variable change (Intelligence? as true and false) due to the cost of running the program with that many agents. Therefore only two simulations took place. The results cannot therefore be seen as conclusive evidence rather as suggestive evidence. Looking at both the percentage of predations and the number of predations shows strong suggestive evidence to back up this theory of correlation to the Control Test.

12.3 The Efficiency of the Intelligence Algorithm

One of the very conclusive findings from the experiments was that the intelligent shark agents successfully predated a higher average of seal agents when compared to the experiment with equivalent variables except with basic navigation shark agents. This is particularly prominent in the four experiments with the ratio of 1:100 sharks and seal; during the first set of experiments with the high density Sector 4 seal population the intelligent shark agents average 7 more predations than the basic shark agents. In the second set of experiments where the seal population densities were more spread the intelligent shark agents still managed an average of 13 more predations than the basic sharks. This is irrefutable evidence that the algorithm optimises the shark feeding and successful predation which supports the theory that white sharks use such a mechanism to optimise their hunting strategy.

The evidence from the other experiments with higher shark population densities are also generally higher with an albeit smaller margin, this can be attributed to the fact that the predation number was reaching the population of the seal agents due to the small ratio of seals to sharks and given a higher population the margins would be larger. As the 1:100 ratio experiments are deemed more realistic and therefore more accurate it makes the original findings more concrete. Furthermore an observation of the individual results during the single intelligent shark agent experiments show that when the shark agent has made a previous predation within the Sector 4 area the total number of predations is significantly higher as the shark will not venture much farther from this sector whereas the basic shark agent can make multiple predations in this area and leave only making a few predations subsequent to this, showing clear optimisation (see Appendices section 16.4 row 4 and 15, section 16.8 row 11 and 13). The total number of predations is directly proportional to the number of predations in the optimal seal agent areas whether the seal group choice is heavily biased toward one sector or not.

12.4 The Relationship between the Seal Group Heading and the Control

When comparing experiment set 1-4 with experiment set 5-8 all experiments in the latter set show positive correlation toward the Control Test for the intelligent agents (Experiments 6 and 8) when compared to the basic agent results (Experiment 5 and 7). However the former set of experiments showed very little difference between Experiments 1 and 2, negative correlation for Experiment 3 with a wide spread of predations and negative correlation for Experiment 4 with over predation of 5.8% and low predations in all other sectors. This supports the theory that the higher the amount of shark agents (and therefore the smaller the ratio) the less significance in the result as over predation leads to simply a representation of the seal agents population of certain sectors rather than the shark's predation strategy. It also suggests that the more accurate large ratio (Experiments 3 and 4) shows overpopulation in the Sector 4 and is an indication that these probabilities of seal group heading (6/8, 1/8, 1/8) are too high and therefore the second set of experiments have more merit. However Experiment 4 does reinforce the idea that the algorithm does single out the highest populated area of seals and therefore make it an efficiency enhancement for the white shark hunting strategy.

12.5 The Relationship between Intelligence and Basic Navigation

This is the most important comparison for the outcome of this research and based on all the conclusions drawn up so far the most accurate and credible experiment to draw upon will be with a high ratio to seals to sharks (1:100 or 1:2481) and with a lower probability of seal group heading choice (4/8, 2/8, 2/8). This suggests the comparison of Experiments 7 and 8, and analysis of Experiment 9. These experiments all show that the intelligence algorithm is positively correlating to the control in comparison to the basic shark. The results are not unanimous throughout all 20 tests which would make for a stronger argument; however the averages do suggest that the intelligence algorithm is closer to real life results than the basic navigation. The extent to which the intelligent agents show correlation to the control compared to the basic navigation agents is not a large margin which was always inevitable with the controlled populations of the seal agents. This does however lead to some provocative final conclusions and directions in which to continue the research.

12.6 Future Work

The shark intelligence algorithm can definitely be refined and improved. Currently each previous predation is stored in a stack structure where old predations are popped off as a new predation is made, holding only four predations. A system of rating each predation on its strength (e.g. successful, unsuccessful, expended energy etc) and then creating a network or map for touring these in order of rank would be an interesting way of improving and expanding the shark's virtual memory bank. As there is a known link between the strength of stimuli and the strength of memory in fish combined with the fact that white sharks have a great capacity to store in long term memory this is a feasible expansion of the algorithm. Building some sort of tour based around the ordered predation and relative distance would be a possible hunting strategy to explore.

Some of the excluded elements of white shark behaviour could be included to increase the accuracy of this or another simulation. For example an expansion into their feeding behaviour as an added positive stimuli, counting where the sharks have fed (not necessarily hunted and killed) on prey or have been outranked socially by a more dominant shark. These could all possibly effect how the shark chooses its areas of possible predation. Increasing the accuracy of the Energy variable in the simulation to a real life measure of energy and time between predations as observed from real life.

There are a great number of expansion possibilities for the seal behaviour mainly regarding their defensive behaviour and grouping strategies (see section 4). Increasing the variety and depth of the seal behaviour will have increased accuracy to the simulation in real life and will provide more accurate and realistic predation results particularly when presented with a realistic ratio of sharks to seals (1:2481). So far the predation count is far higher than observed by Martin in comparison; one thing that would be useful at improving real life accuracy is the introduction of vigilance.

If a different ecosystem were to be used as a basis of a similar simulation with a more even spread of seal activity in the surrounding waters it would make for interesting analysis of shark movement. As there is an even spread of seal activity there is no obvious area to occupy or frequent, therefore observations of sharks frequently returning to an area of previous predation whilst having no follow up success would be a stronger indicator that sharks use memory to calculate their next location rather than immediate sensory information such as chemoreception and olfaction.

12.7 Discussion

From the conclusions drawn up so far there is some hard evidence and some strong suggestive evidence. The hard evidence is that the intelligence algorithm proposed leads to unanimously higher predation numbers, especially with a more accurate shark to seal ratio, and from individual results shows that high predation occurs within the most densely populated sector, and a lower predation count occurs when the shark's hunting is spread over the other sectors. This shows that this intelligence algorithm has greater efficiency than a basic shark algorithm, suggesting that using memory as a tool to increase the likelihood of predation is successful and **could** be something employed by white sharks. The suggestive evidence that this could be employed by white sharks is in the positive correlation found when comparing Experiments 7 and 8 and when looking at Experiment 9. Therefore this idea of sharks using memory to premeditate attacks on Cape fur seals should be subject to further research, ideas for such research are listed in the following section.

The significance of understanding how sharks choose to predate leads to a better understanding of the feeding and preservation of a species under threat. If the hypothesis (1) of white sharks indeed premeditating attacks on their prey is proven correct, this could explain the problems encountered when keeping a white shark in captivity [Monterey Bay Aquarium, 2008] as a small area with no landmarks or celestial cues or any regularity of prey movement possibly prevents or discourages the shark from feeding off carcasses. It is possible the white sharks become disorientated or struggle to recognise areas of their habitat when there is little to differentiate any areas in a confined tank. Equally there are arguments that the lack of sensory information that come with carcass feeds for example there may be a lack of olfaction and chemoreception information on a carcass compared to a fresh kill and there is a distinct lack of hydrodynamic stimuli that would be otherwise displayed by live prey which is something proven vital in white shark predation [J Engelmann et al, 2000]. There is also an argument of an inanimate object such as a carcass being less attractive compared to living objects that exude electromagnetism [R S Collier et al, 1996]. This misrecognition of food would perhaps lead to less exploratory bites [E Ritter et al, 2004] and therefore less successful feeding due to not determining the palatability of the carcass. Regardless of the reasons why white sharks frequently fail to feed in captivity, whether it be the lack of sensory information leading to misrecognition, the irregularity in the shark hunting sequence of recognition, killing and feeding or the lack of routine in feeding and disorientation it is clear that white sharks will remain an enigma to study.

It is also suggested by the findings in this paper, that fish memory occurs when a strong emotion is evoked by a positive stimuli such as predation. Therefore there is a direct link between predation and shark memory, which means it is conceivable that because there is no predation in captivity white sharks find difficulty associating environmental areas and predation and therefore cannot build a neural map of their surroundings when in captivity. This is further evidence that small ecosystems such as Seal Island that white sharks rely heavily on for feeding and navigation are paramount to the preservation of the white shark species and it is therefore equally important that the preservation and protection of such small ecosystems continue.

There are also some other findings from the results that can be concluded that we not expected but nonetheless still of some worth. One of the most notable things to stand out from the results was the success of the intelligent agents to successfully predate higher total of seal agents unanimously in each pair of experiments, with specific reference to the directly proportional relationship of high total predations and high predations in sector 4. This means that over each of the twenty iterations of the experiment when a high total number of predations occur then the percentage of predations is usually distinctly high in sector 4, whereas when a low or average number of total predations occur there is usually a more even spread of percentage predations over the 6 sectors. This proves that the intelligence algorithm is indeed an optimal means of successful predation in this environment. This would be interesting to test in other real world ecosystems with different prey dynamics. Another interesting thing to note is the probability of the seal group choice of direction, with an rough estimate of 4/8 change of sector 4, 2/8 sector 3 and 2/8 other sectors, however I feel this could be refined to 4/8 sector 4, 3/8 sector 3 and 1/8 other sectors as the results in sector 3 were consistently too low. This would need further investigation and experimentation, the ABM simulation presented here would be an adequate application for this.

12.8 Summary

I'll now attempt to summarise what has been achieved in relation to the objectives set at the start of this project;

- **Comprehensively understand the behavioural patterns and predatory strategies of the white shark through research papers and other means of secondary research.**
  - Understanding of the white sharks decision process when hunting as well as migration and other behaviour patterns have been discovered. A decision tree (Fig 1) was proposed of the decision process of the shark when premeditating an attack as well as a three phase action process detailing the predatory interaction (Fig 2) was proposed.
- **Create hypotheses of how the white shark may be able to premeditate prey movements using secondary research as a basis.**
  - Four hypotheses were devised at various levels of detail regarding the specifics of the simulation. The hypothesis (1) proposed in the title, regarding the ability of white sharks to premeditate attacks on their prey. The second hypothesis (2) is a detailed hypothesis regarding Cape fur seals and returning to areas of premeditation at Seal Island. The last hypotheses (3) and (4) regard the specifics of the simulation in relation to Martins findings.
- **Use these hypotheses as a basis for the design and implementation of an ABM to be proven or disproven.**
  - Hypotheses (2), (3) and (4) have been proven by the results that show strong suggestive and hard evidence of correlation between intelligent shark agents that return to areas of predation to premeditate attacks with Martins findings. Hypothesis (1) can only be proven by hard observational evidence.
- **Create an ABM that accurately represents the behavior of white sharks and Cape fur seals to the extent of the relevance to the investigation into white shark premeditation.**
  - Accurate behaviour of both sharks and seals were derived in the implementation section 8 and these were broken into decision trees, which are directly transferable into code (see appendices section 15)
- **Create experiments from the finished model that will provide data from which information can be derived regarding the behaviour and actions of the predator and prey which can lead to conclusions of these results regarding if and how premeditation of prey movement occurs by the white shark.**
  - Experiments were devised to test the hypotheses that had been made in section 10 using various variables that were changed individually for each experiment, resulting in 8 experiments and an added 9th. Conclusions were drawn from these individually resulting in the best shark to seal ratio as 1:100, and an ideal seal group movement probability of (4/8) (2/8) (2/8) and the hypotheses (2) (3) and (4) being concluded proven with strong suggestive and hard evidence from the results.
- **Improve knowledge of white shark behaviour from the information derived from the results generated from the ABM simulation.**
  - From concluding that there is strong evidence to suggest that white sharks can use long term memory and cognitive decision to optimise their premeditative attacks on pinnipeds gives improved knowledge of the white shark's hunting techniques and cognitive abilities. This will

hopefully lead to better understanding of how the white shark has remained the most successful predators for hundreds of years as well as how such cognition can perhaps cause confusion or disorientation for sharks in captivity with no celestial cues or any predation routines or repetition.

- **Provide ideas for future research if relevant from the conclusions.**
  - Accurate behaviour of both sharks and seals were derived in the implementation section 10 and these were broken into decision trees, which are directly transferable into code (see appendices section 15)

To summerise all achievements and findings in this report, the first place to start is by the categorisation of ‘premeditation’ from the initial hypothesis of ‘the white shark’s ability to premeditate attacks on Cape fur seals’ into three categories, and recognising that the obvious choice of investigation was ‘The prediction of spatial areas and time periods where predation is highly likely or most likely to occur within an ecosystem’. This lead to the discovery of the possibility of white sharks being able to remember areas of an ecosystem [J Topál et al, 1999] when presented with certain stimuli [J Topál et al, 1999] and that contrary to popular belief many fish actually have superb long term memory [V Csányi, 1989]. This lead to the development of a possible neural network devised that could effect which direction a white shark could head if a particular area of previous predation was introduced as the reinforcement signal P (Fig 3) [A.G Barton et al, 1981].

It was then found that animats were a transition from an animal to simulation robot, and that these animats could be interpreted as agents in an Agent Based Model. Such agent based models as ‘Boids’ [U Wilensky, 1999] have shown how when simple laws or ‘rules’ are allocated to these agents astounding results can be obtained with unquestionable similarity to reality. From this the idea that by comparing real life observations of predations in a specific eco system with those from shark animats in an ABM then conclusions to the validity of the original hypothesis of white sharks premeditating attacks on Cape fur seals.

The development of the ABM simulation then took shape as the non-functional requirements were defined and from this the conclusion that NetLogo 4.0.4 would be used to create the ABM simulation. This then generated a list of functional requirements to define the specification of the simulation. Once this was done the implementation was documented with defined constants and variables that would later be used in the experimentation phase. Behavioural models for both the shark and seal agents were defined using a module-based hierarchy with transient states for the seals behaviour, and a functional-based hierarchy with dependant variables for the shark behaviour. Each module and function were broken into decision trees respectively with all specific circumstantial decisions defined. It was then presented that each seal and shark agent would concurrently run through each of their respective behavioural model each ‘tick’ until the tick counter was reached. The implementation was then thoroughly tested using both black-box and white-box testing against the requirements that had been defined.

Following the successful implementation phase, the experimentation phase began by officially defining the four hypotheses that were to be proven or disproven based on all the work done so far. The method was then described with the three main variables that were to be changed and how these would effect the result of the experiment individually. From these eight experiments were completed twenty times and then the results taken of the average and presented. Initial analysis of these results showed that the most convincing results were from the variables; white shark Intelligence (true), shark to seal ratio 1:100 and seal group direction probabilities (4/8 sector 4, 2/8 sector 3, 2/8 random sector). A ninth experiment was devised with these variables except the shark to seal ratio was 1:2841 (an exact representation of Martin’s recorded shark to seal ratio).

These results then proved for interesting analysis and conclusion, concluding that when the shark population is unrealistically high then the results become indistinguishable, also that the intelligence algorithm is undoubtedly optimal in overall total predations compared to the basic sharks and that the probability of seal groups choosing an direction travel in is close to (4/8 sector 4, 2/8 sector 3, 2/8 random sector) but needs further investigation. Primarily what was concluded is that from these findings Experiment 7 and Experiment 8 were the most valid and provided evidence that white sharks do indeed use intelligence to return to areas of previous predation to optimise their hunting strategy. Something this was supported by the results of Experiment 9, also showing positive correlation towards Martin's findings compared to those of the basic shark who randomly navigated the sea.

From these conclusions the discussion of these findings lead to the idea that white sharks could find difficulty in captivity due to the lack of celestial cues or terrain that could make up the cognitive map of their environment and cause disorientation or lack of familiarity, something which is in abundance in ecosystems such as Seal Island. It was also suggested that the lack of routine hunting patterns such as the intelligence algorithm suggested would lead to poor feeding habits as well as the lack of sensory stimulation with carcasses compared to live prey at an ecosystem such as Seal Island, with an approximate 60,000 live seals.

From this it was concluded that the conservation of such eco systems as Seal Island is paramount to the conservation of white sharks and that much further research into white shark predation and feeding behaviour is needed before captivity of white sharks improves. When this happens, observation, learning and improved protection of the threatened species is required so that the legacy of the 65 million year old predator can continue.

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14. Glossary

ABM – Agent Based Modelling

Animat – A representation of an animal combined with an autonomous robot.

Agent – A virtual representation of an individual.

Agent Based Simulation – A dynamic system of interacting agents.

Celestial Cues – A recognisable object or area in the sky or above sea level.

Cetaceans – A group of marine mammals including the whales and dolphins.

Chelonians – A representation of a group of reptiles including the tortoises and turtles.

Chemoreception – A means of chemically analysing or recognizing something.

Complex System – A multi agent system with interweaved agents and environment.

CSV – Comma Seperated Value format where text values are separated by a comma.

Design Flaws – Errors in the design of the program that cause major programming change

Fleeing – The description of an individual evading a predator by means of physical escape.

Flocking – When a group of prey flee from a predator.

Grouping – A mechanism used across multiple species where individuals form a close collection, often travelling together and altering one another of predators. Used as a defence mechanism but can also often encourage breeding or preserve body temperature.

Juvenile – A pup or young adult male or female pinniped.

Lateral Line – A series of sensory pores along the head and sides of fish and some amphibians by which water currents, vibrations, and pressure changes are detected.

Logic Bugs – Errors in programming code that appear when the program is run, after compilation.

Multi Agent System – A simulation based around multiple agents interacting.

Mobbing – A mechanism used across multiple species by with a group of prey act aggressively toward their predator as a deterrent.

Neural Network – A real or virtual device, modelled after the human brain, in which several interconnected elements process information simultaneously, adapting and learning from past patterns.

Olfaction – The sense of smell. For water-dwelling organisms, e.g., fish or crustaceans, the chemicals are present in the surrounding aqueous medium.

Philopatry – The ability for an individual to return to the exact location of its birthing for breeding.

Pinniped – A representation of the group of mammals including seals, sea lions, and walrus.

Stimulus - Something causing or regarded as causing a response.

Vigilance – Alert watchfulness in relation to a predator or breeding.

Part IV
Appendices

15. Code Listing

15.1 Move Forward

```
to move_forward
ifelse patch-ahead 2 != nobody and [land = 0] of patch-ahead 2
  [ifelse any? patches in-cone 6 360 with [land = 1]
    [forward 1]
    [facexy Destdx Destdy
     forward 1]]
  [ifelse patch-left-and-ahead 45 2 != nobody and [land = 0] of patch-left-and-ahead 45 2
     [set heading heading - 45
      forward 1]
     [ifelse patch-right-and-ahead 45 2 != nobody and [land = 0] of patch-right-and-ahead 45 2
       [set heading heading + 45
        forward 1]
       [ifelse patch-left-and-ahead 90 2 != nobody and [land = 0] of patch-left-and-ahead 90 2
          [set heading heading - 90
           forward 1]
          [ifelse patch-right-and-ahead 90 2 != nobody and [land = 0] of patch-right-and-ahead 90 2
           [set heading heading + 90
             forward 1]
            [ifelse patch-left-and-ahead 135 2 != nobody and [land = 0] of patch-left-and-ahead 135 2
              [set heading heading - 135
               forward 1]
              [ifelse patch-right-and-ahead 135 2 != nobody and [land = 0] of patch-right-and-ahead 135 2
               [set heading heading + 135
                forward 1]
               [set heading heading + 180
                forward 1
                set move-iteration 299]
             ]
            ]
          ]
        ]
      ]
  ]
set move-iteration move-iteration + 1
set energy energy - 1
end
```

15.2 Predate

```
to predate
if any? seals-here
  [ifelse random 2 = 1
     [ask seals-here [die]
      set Predation Predation + 1
      set personal-predation personal-predation + 1
      if sector = 1
        [set Sector1 Sector1 + 1]
      if sector = 2
        [set Sector2 Sector2 + 1]
      if sector = 3
        [set Sector3 Sector3 + 1]
      if sector = 4
        [set Sector4 Sector4 + 1]
      if sector = 5
        [set Sector5 Sector5 + 1]
      if sector = 6
        [set Sector6 Sector6 + 1]
      if sector = "border"
        [set Border Border + 1]
      ifelse personal-predation = 1
      [set PrevPredationdx1 pxcor
       set PrevPredationdy1 pycor]
       [ifelse personal-predation = 2
        [set PrevPredationdx2 pxcor
         set PrevPredationdy2 pycor]
         [ifelse personal-predation = 3
           [set PrevPredationdx3 pxcor
            set PrevPredationdy3 pycor]
           [ifelse personal-predation = 4
             [set PrevPredationdx4 pxcor
              set PrevPredationdy4 pycor]
             [if personal-predation > 4
               [ifelse personal-predation mod 4 = 1
                 [set PrevPredationdx1 pxcor
                  set PrevPredationdy1 pycor]
                 [ifelse personal-predation mod 4 = 2
                   [set PrevPredationdx2 pxcor
                    set PrevPredationdy2 pycor]
                   [ifelse personal-predation mod 4 = 3
                     [set PrevPredationdx3 pxcor
                      set PrevPredationdy3 pycor]
                     [if personal-predation mod 4 = 0
                       [set PrevPredationdx4 pxcor
                        set PrevPredationdy4 pycor]
                     ]
                   ]
                 ]
               ]
```

```
            ]
          ]
        ]
      ]
    set energy 100
    ]
    [set heading heading + 180]
  ]
end
```

15.3 Set a Group Heading

```
to set_group_heading
let temp random 8
ifelse temp < 4
  [ifelse random 2 = 1
    [set Destdx random -107
     set Destdy -132
     facexy Destdx Destdy]
    [set Destdx -106
     set Destdy random -133
     facexy Destdx Destdy]]
  [ifelse (temp = 4) or (temp = 5)
    [ifelse random 2 = 1
      [set Destdx random 107
       set Destdy -132
       facexy Destdx Destdy]
      [set Destdx 106
       set Destdy random -133
       facexy Destdx Destdy]]
    [if (temp = 7) or (temp = 6)
      [right random 360]
    ]
  ]
end
```

15.4 Form a Group

```
to form_group
ifelse state = 0
  [set state 3
   set Destdx [pxcor] of one-of patches with [land = 1]
   set Destdy [pycor] of one-of patches with [land = 1]
   facexy Destdx Destdy
   set group random 12
   while [group < 5]
     [set group random 12]
   set groupsize 1
   forward 1]
  [if state = 3
    [ifelse Destdx = pxcor and Destdy = pycor
      [set Destdx [pxcor] of one-of patches with [land = 1]
       set Destdy [pycor] of one-of patches with [land = 1]
       facexy Destdx Destdy
       forward 1]
      [forward 1]
    if any? other seals in-cone 4 270[
      if [my-out-links = no-links and my-in-links = no-links and (state = 0 or state = 3)] of one-of other
seals in-cone 4 270
        [without-interruption [
         set leader 1
         ask one-of other seals in-cone 4 270 with [my-out-links = no-links and my-in-links = no-links
and (state = 0 or state = 3)]
           [set leader 0
            create-link-from myself [tie]
            set state 4
            set group 0
            set groupsize 0]]
          set groupsize groupsize + 1]]
    if (grp-increment > 150) or (groupsize >= group)
     [if leader = 1 [
       set_group_heading
       set state 4
       set group 0
       set groupsize 0
       set grp-increment 0]]
  set grp-increment grp-increment + 1]]
end
```

16. Results Tables

16.1 Experiment 1

Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6	Predations
6	13	12	50	7	4	94
3	7	13	41	23	3	96
3	9	11	51	16	2	95
0	14	9	59	9	3	98
9	12	20	40	7	4	98
3	4	24	39	17	6	91
8	8	12	38	16	8	91
4	17	14	46	9	2	96
6	16	13	34	11	9	96
6	6	10	54	12	7	96
6	4	11	53	9	6	95
7	5	21	44	12	3	96
4	8	12	57	6	3	94
8	12	7	52	5	6	98
8	3	12	57	5	5	95
6	13	15	48	5	4	92
3	3	18	36	26	5	96
6	9	12	52	9	3	95
8	10	17	40	8	4	93
5	8	11	53	5	5	94
5.45	**9.05**	**13.7**	**47.2**	**10.85**	**4.6**	**94.95**

16.2 Experiment 2

Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6	Predations
3	10	11	57	12	3	95
13	6	12	43	8	2	96
12	15	11	42	6	7	96
6	15	15	47	6	2	97
5	8	17	46	9	3	95
3	9	24	42	11	4	97
4	7	4	52	14	8	98
6	13	20	39	6	7	97
2	4	17	52	7	2	95
6	6	25	45	6	0	93
7	4	15	53	6	5	97
10	11	12	46	6	5	95
6	24	13	28	9	7	98
6	10	7	44	15	9	97
14	4	7	57	10	4	100
7	7	6	56	12	0	95
12	4	10	51	10	3	95
3	7	8	51	13	7	97
7	17	7	42	10	3	96
2	7	12	62	8	1	95
6.7	**9.4**	**12.65**	**47.75**	**9.2**	**4.1**	**96.2**

16.3 Experiment 3

Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6	Predations
0	7	17	60	7	3	28
3	7	3	57	17	3	28
2	5	2	53	0	23	39
3	0	12	68	3	3	32
15	2	13	52	2	5	38
4	25	33	29	4	0	24
16	0	25	41	12	4	24
7	19	0	50	11	7	26
0	11	5	83	0	0	18
7	21	21	28	7	7	14
0	0	17	46	25	0	28
13	4	27	36	0	9	22
19	11	19	23	15	0	26
3	9	24	30	9	12	33
9	28	0	47	2	2	42
0	16	8	50	8	5	36
10	10	10	28	25	10	28
6	6	12	60	12	0	33
14	3	40	29	3	3	27
0	25	6	54	3	0	31
6.55	**10.45**	**14.7**	**46.2**	**8.25**	**4.8**	**28.85**

16.4 Experiment 4

Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6	Predations
2	0	2	57	32	0	40
2	4	2	70	0	9	41
0	0	19	58	0	5	36
0	0	0	100	0	0	17
6	0	4	23	46	4	47
2	2	10	67	8	0	49
5	3	35	39	10	1	56
4	14	2	76	0	2	50
0	2	0	70	18	0	50
11	27	2	37	6	0	43
6	10	0	58	18	0	48
0	4	20	40	24	2	50
0	0	13	78	2	0	37
0	0	8	83	0	0	37
0	0	1	92	0	0	52
7	11	38	30	7	0	26
0	0	0	54	34	2	46
6	2	11	60	20	0	45
3	3	37	56	0	0	32
0	6	28	50	10	0	46
2.7	**4.4**	**11.6**	**59.9**	**11.75**	**1.25**	**42.4**

16.5 Experiment 5

Sector1	Sector2	Sector3	Sector4	Sector5	Sector6	Predations
17	13	7	44	4	4	95
2	15	15	41	10	5	94
8	8	34	33	11	1	95
4	12	19	45	5	6	94
2	8	27	44	3	4	93
13	11	6	48	3	5	94
5	11	27	42	2	7	95
13	14	32	23	4	6	90
9	6	16	43	10	10	99
9	10	26	39	5	7	98
5	11	24	45	3	6	98
7	15	9	42	7	14	99
9	20	13	45	4	0	94
5	6	14	38	21	8	95
4	5	29	36	10	4	98
2	18	21	34	7	7	90
10	11	20	28	6	11	94
2	8	18	43	12	12	97
4	14	13	48	8	8	96
20	12	17	31	4	5	94
7.5	**11.4**	**19.35**	**39.6**	**6.95**	**6.5**	**95.1**

16.6 Experiment 6

Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6	Predations
8	2	18	54	8	3	98
8	13	22	42	8	1	96
7	7	8	39	23	8	96
16	11	9	42	2	5	98
11	8	21	36	8	4	93
4	16	22	33	12	0	96
0	9	21	44	13	4	93
8	16	14	35	12	3	95
8	16	14	35	12	3	95
4	15	33	27	2	8	96
7	11	29	34	6	3	99
2	6	31	43	9	3	96
4	7	23	55	0	2	99
8	11	27	46	3	0	97
8	8	24	36	5	8	98
7	15	24	28	12	3	95
3	12	27	37	4	3	94
1	5	11	59	7	7	94
9	8	19	45	7	4	93
3	10	22	34	17	4	97
6.3	**10.3**	**20.95**	**40.2**	**8.5**	**3.8**	**95.9**

16.7 Experiment 7

Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6	Predations
0	31	34	21	12	0	32
0	22	27	44	0	0	18
7	0	21	35	0	32	28
0	0	45	41	4	8	24
0	2	22	58	8	0	36
0	0	22	77	0	0	22
0	21	46	0	10	10	28
8	6	25	45	8	2	48
18	4	13	59	4	0	22
0	11	0	33	0	33	18
19	13	27	27	5	0	36
10	15	15	0	10	21	19
4	9	27	45	4	4	22
9	9	45	27	4	0	22
4	12	28	24	16	4	25
3	0	26	46	15	7	26
5	10	21	47	10	0	19
4	12	36	44	4	0	25
6	3	17	34	13	13	29
3	12	22	35	25	0	31
5	**9.6**	**25.95**	**37.1**	**7.6**	**6.7**	**26.5**

16.8 Experiment 8

Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6	Predations
10	50	25	10	0	0	20
12	56	10	0	5	2	39
13	0	6	35	11	24	45
0	0	14	85	0	0	48
9	26	7	48	2	2	41
3	11	29	44	3	3	27
9	32	19	22	0	0	31
15	59	6	0	0	9	32
3	3	10	73	0	0	30
0	12	38	33	10	5	39
3	0	3	92	0	0	28
0	0	25	65	8	0	35
0	0	0	100	0	0	39
0	5	16	66	1	3	60
0	12	37	37	10	0	48
0	2	0	77	2	11	36
0	25	7	50	3	3	28
8	8	6	75	0	0	48
10	0	28	45	0	0	46
2	0	2	91	2	0	34
.85	**15.05**	**14.4**	**52.4**	**2.85**	**3.1**	**37.7**

17. Test Lists

17.1 Seal Movement Continued

Module 3: lets_frolic
Test 3.1: Test lets_frolic identifies state 0 and runs commands to set state, frolic iteration, new destination out to sea and moves forward.
Expected: A black patch should be set for the new destination, the state should be printed as 2, the frolic iteration counter should print as 1, and all seals should then move forward then halt.
Result: Expected
Passed

Test 3.2: Test if seal agents successfully travel to set destination
Expected: The set destination should occur as in Test 3.1, the seal should then iteratively move toward the white destination square, when this is reached by the seal agent this will then turn black, and then halt.
Result: Expected
Passed

Test 3.3: Test if the second destination if the second destination, out at sea, of the iteration is chosen.
Expected: A new patch colour for the second destination should appear as the first destination turns black from Test 3.2. When this second destination is reached the patch colour of this destination should then return to the original sea colour.
Result: Expected
Passed

Test 3.4: Test if the final home destination, the home patch of the individual agent on land, is chosen and reached by the seal agent.
Expected: The Tests 3.1 - 3.3 should successfully complete then the home destination should appear as a red patch on the environment, this should be on land. Once this is reached it will return to the original land colour and then halt. The state shown should then be 0 (neutral).
Result: Expected
Passed

Test 3.5: All debugging devices removed, lets-frolic should work as expected.
Expected: Seal agents should frolic by travelling to two random out at sea destinations then return to their home patch and return to a neutral state.
Result: Expected
Passed
Module Passed

Inter-Module Testing: move_seals, do_nothing and lets_frolic
Test M1: Testing that the three modules work in unison as designed
Expected: The function move_seals should perform random assignments of tasks for seal agents, which should be either do_nothing, lets_frolic or turn pink (imitating travel away). The do_nothing function should turn agents yellow and keep them static for 20 seconds of wait, then return them to black colour returning to state 0. The function lets_frolic should cause seals to turn green and frolic as described in Test 3.5, then return the state to 0 and the agent will return to being black. The function form_group will only turn the seal pink briefly then return to a state 0. These should all occur concurrently and cyclically.
Result: When running the seals from a concurrent function the agents did not run concurrently it is a simulated concurrency using a turn taking mechanism. This meant that the agents calling do-nothing slowed all agents regardless of which function they were calling. This meant the module was changed to an iterative cycle without any wait and using a iterations counter and introducing a new state 5 (do nothing). This simulated the 20 seconds wait.
Condoned Pass

Module 4: form_group
Test 4.1: Testing if the input state of Neutral will do all the correct tasks
Expected: Show state 3, set a white patch on land for each agent to travel to, show the group assigned to it between 5-11, and then print the group size of 1 then move toward its destination one square.
Result: Expected
Passed

Test 4.2: Testing if the input state 3 (form group) new destinations are picked when current ones are reached.
Expected: The patch colour of destinations should turn black and be on land and then turn back to their original colour when reached. There is no iteration counter as this a cyclic process and should repeat.
Result: Expected
Passed

Test 4.3: Testing if the filter to only create and link to seal agents with no previous link and with a state of either 0 (neutral) or 3.
Expected: The seal agents assigned with alternative states or within groups should not have links created to them whilst those with the correct state and without any current links (without being part of a forming group) should be linked.
Result: Expected
Passed

Test 4.4: Testing whether ties form within the given cone of sight for the seal
Expected: A white link will form between the two agents, this will be tied to the leaf seal from the root seal, the root seal will remain black and the leaf seals will turn white. The leader will then continue to destination(s) until all agents of the group are filled. Then halt.
Result: Expected
Passed

Sub Module 4.1: set_group_heading
Test 4.1.1: Test if South West random field is chosen with the correct bias 20/25
Expected: The South West outer patches of the environment should change colour to yellow 20/25 of the time.
Result: Expected
Passed

Test 4.1.2: Test if South East area of the environment is chosen with the correct bias 4/25
Expected: The South Eastern outer patches of the environment should change colour to red 4/25 of the time.
Result: Expected
Passed

Test 4.1.3: Test if a random heading chosen with the correct bias 1/25
Expected: A printed test message will print when the random heading code has run with 1/25 of the time.
Result: Expected
Passed

Test 4.1.4: Tests that set_group_heading function operates fully.
Expected: Should run Tests 5.1.1-3 without fault and cycle.
Result: Expected
Passed

Inter-Module Testing: form_group and set_group_heading
Test M2: Testing seals should operate and form a fully formed group up to their given group number then set a heading using the sub module set a heading for the group.
Expected: The leader seal should set the heading and should gather the other members of the group, once the group target size is met the heading should be set and the appropriate patch should then turn yellow, red or be given a random heading.
Result: All worked as expected except for a loop found in the form_group function where a seal or group of seals will be searching to fill the group size when there are no seals available and therefore get stuck in a infinite loop. This was solved by using an iterative counter that assigns the group to leave and assigns all seals a state of 4 (travel away).
Condoned Pass

Inter-Module Testing: move_seals, do_nothing, lets_frolic, form_group and set_group_heading
Test M3: Testing the top down run using the full functions of do_nothing, lets_frolic and form_group.
Expected: The function move_seals will assign the functions according to their probability all functions will operate correctly. The function do_nothing will turn the agent yellow, lets_frolic will turn the agent green and form group will form a group of agents from those available then set a heading before halting. This means all agents will eventually get to this state, then halt.
Result: Expected.
Passed

Module 5: travel_away
Test 5.1: Test that the root seal follows to the destination and the leaf seals follow in the same direction
Expected: The root seal will follow step by step toward its destination and the leaf seal agents will follow it closely without deviating from the course and will be "pulled along" by the individual tied links.
Result: Expected
Passed

Test 5.2: Test that the root seal can find the outer edge and therefore exit the process of travelling away
Expected: Root seal will detect the outer edge (its destination) and therefore become hidden and set its state to neutral (hidden) and will do likewise to the rest of the group. The state 0 will be printed for each seal once it has become hidden.
Result: Expected
Passed
Modules Passed

Module 6: travel_back
Test 6.1: Test input state 0 (neutral hidden)
Expected: The state will change to 1 (travel back) which will be printed, the seal will become visible as will the other seals linked to the root seal, the color of all seals will be blue, sets the destination as the home patch which will turn white.
Result: Expected
Passed

Test 6.2: Test input state 1 (travel back) once at the home patch
Expected: Checks if the destination is reached by turning the white patch in Test 6.1 to black once the seal agent arrives.
Result: Expected
Passed

Test 6.3: Test the function of the group disbanding once arrived
Expected: Sets the state 0 (neutral) of the root agent which is printed, sets the root variable (leader) back to 0 which is printed, sets all leaf agents as root agents (see Test 6.4), kills all links which is a visible verification. Also resets the groupsize which is printed as 0 and resets group variable which is printed as 0.
Result: Expected
Passed

Test 6.4: Testing leaf agents become root agents and navigate back to their home destination.
Expected: The leaf agent will now become active; their home destinations are shown with a white patch which turns black once the agent reaches it. The state is then set to 0 (neutral) which is printed as 0.
Result: Expected
Passed
Module Passed

Inter-Module Testing: All modules
Test M4: Testing the function of all modules
Expected: All modules should behave as described in the individual sections of the module testing, including sub modules, each individual state should turn the seal colour (neutral black, travel back blue, travel away red, frolicking green, doing nothing yellow, forming group pink, formed group (root) black, formed group (leaf) white. This process is cyclic and should repeat.
Results: Expected.
Passed
All Seal Movement Modules Passed

17.2 Shark Movement Continued

Module 2: basic_shark
Test 2.1: Testing that shark agents choose a random patch to move to without moving on land.
Expected: Shark agents should move in a random motion choosing a random neighbouring patch to move to without moving on land.
Result: Expected
Passed
Module Passed.

Module 3: predate
Test 3.1: Testing that when seal and shark agents are on the same patch that seal agents die
Expected: All seal agents will die and be removed from the environment leaving only the shark agents. Then halt.
Result: Expected
Passed

Test 3.2: Test that 50% of the time shark agents fail to predate and 50% of the time they succeed.
Expected: Approximately half the seal agents will disappear from the environment and die; approximately half will remain on the environment. Then halt.
Result: Expected
Passed

Inter-Module Testing: basic_shark, predate
Test M1: Testing the predate module's ability to store 4 previous predations and continue to replace old stored predations with new predations as they are made.
Expected: A single shark agent will move in a random direction, as predations are a coloured patch is left behind where the colour is dependant on how the predation has been stored. There is room for four previous predations which are replaced as new ones are made which will result in new coloured squares as new predations are made. The order is as follows; PrevPredation1 = yellow, PrevPredation2 = green, PrevPredation3 = red, PrevPredation4 = blue.
Result: Expected
Passed
Predate Module Passed.

Inter-Module Testing: move_sharks, basic_shark, predate
Test M2: Testing that the movement of sharks with basic intelligence function as expected.
Expected: The **move_sharks** function will allow sharks to locate, premeditate attacks and attack seal agents while the **basic_shark** module will allow sharks to move randomly around the map without navigating on land and the predate function will allow shark agents to record a predation and cause seal agents to die if the predation is successful.
Results: Expected.
Passed

Module 4: set_new_dest
Test 4.1: Test that a random destination is chosen in the sea when the energy of the calling shark agent is < 20.
Expected: A shark agent will set a white patch as its destination as a random patch.
Result: Expected
Passed

Test 4.2: Test that after no predations and energy < 20 that the shark agent sets a new random patch.
Expected: A shark agent will set a white patch as its destination as a random patch when no predations have occurred and the energy is less than 20.
Result: Expected
Passed

Inter-Module Testing: move_sharks, set_new_dest, predate
Test M3: Test that after one predation **set_new_dest** sets the new destination as its only previous predation
Expected: A shark agent with < 20 energy and one previous predation will highlight its new destination as a yellow patch indicating that its new destination is its only previous predation. Then halt.
Result: Expected
Passed

Test M4: Test that after two predations **set_new_dest** sets the new destination as the closest previous predation to its current position.
Expected: A shark agent with < 20 energy and two previous predations will highlight its new destination as either a yellow or green patch indicating that its new destination is one of its two previous predations. Then halt.
Result: Expected
Passed

Test M5: Test that after three predations **set_new_dest** sets the new destination as the closest previous predation to its current position.
Expected: A shark agent with < 20 energy and three previous predations will highlight its new destination as either a yellow, green or red patch indicating that its new destination is the closest of its three previous predations. Then halt.
Result: Expected
Passed

Inter-Module Testing: move_sharks, set_new_dest (four_previous), predate
Test M6: Test that after four predations **set_new_dest** calls **four_previous** which sets the new destination as the closest previous predation to its current position.
Expected: A shark agent with < 20 energy and four previous predations will highlight its new destination as either a yellow, green, red or blue patch after set_new_dest calls its sub module four_previous to calculate and delegate the closest of the four previous predations. Then halt.
Result: Expected
Passed
Modules set_new_dest and four_previous passed

Module 5: move_forward
Test 5.1: Check that when given a destination patch the move_forward function can iteratively move to the correct destination.
Expected: A white patch is assigned as the shark agent's destination, the shark agent will move forward until it reaches the destination and when it reaches the patch it will turn black
Result: Expected
Passed

Test 5.2: Check that when given a destination patch the move_forward function can iteratively move to the correct destination and circumnavigate any land obstacles.
Expected: A white patch is assigned as the shark agent's destination, the shark agent will move forward until it reaches the destination and if it encounters any land mass the agent will be able to find a way around the object and then continue on its course to the destination until it is reached.
Result: Expected
Passed
Module Passed.

Inter-Module Testing: move_shark, set_new_dest (four_previous), predate, find_second, move_forward
Test M7: Testing that all modules of the intelligent shark agent work together as expected and that the modules find_second works as expected where move_shark calls set_new_heading (four_previous), move_forward and find_second functions.
Expected: The modules move_shark, set_new_heading (four_previous), predate and move_forward should work as shown in Tests 1.1 – 5.2, the module find_second should be called by move_sharks when the first previous predation is reached where either a new random heading is set or a second previous predation is allocated based on the shortest distance to the current position.
Result: Expected
Passed

Inter-Module Testing: move_shark, set_new_dest (four_previous), predate, find_second, find_third, move_forward
Test M8: Testing that all modules of the intelligent shark agent work together as expected and that the module find_third works as expected where move_shark calls set_new_heading, move_forward and find_second functions.
Expected: The modules move_shark, set_new_heading (four_previous), predate, move_forward and find_second should work as shown in Tests 1.1 – M7, the module find_third should be called by move_sharks when the second consecutive previous predation is reached where either a new random heading is set or a third previous predation is allocated based on the shortest distance to the current position.
Result: Expected
Passed

Inter-Module Testing: move_shark, set_new_dest (four_previous), predate, find_second, find_third, find_fourth, move_forward
Test M9: Testing that all modules of the intelligent shark agent work together as expected and that the module find_fourth works as expected where move_shark calls set_new_heading, move_forward, find_second and find_third functions.
Expected: The modules move_shark, set_new_heading (four_previous), predate, move_forward, find_second and find_third should work as shown in Tests 1.1 – M8, the module find_fourth should be called by move_sharks when the first previous predation is reached where either (depending n the energy of the shark) a new random heading is set or a second new previous predation is allocated based on the shortest distance to the current position.
Result: Expected
Passed

Inter-Module Testing: All shark movement modules
Test M10: Testing that all modules of both the intelligent and basic shark agents work as expected and as described in Tests 1.1 – M9 of the shark movement tests.
Expected: If the 'Intelligence?' variable is set to true then the shark agents should behave as expected in Test M9 otherwise if the 'Intelligence?' variable is set to false then the shark agents should behave as expected in Test M2.
Result: Expected
Passed
All shark movement modules passed