Bird repellents for pest control baits

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Abstract

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Poisonous baits are successfully deployed over large areas of New Zealand to control mammalian pests such as brushtail possums (*Trichosurus vulpecula*) and rats (*Rattus* spp.). While poison-based control leads to positive ecological and disease control outcomes, non-target native birds, such as robins (*Petroica australis*) and tomtits (*Petroica macrocephala*), are sometimes killed after eating bait. In this thesis, I investigated the use of primary and secondary repellents to prevent non-target birds from feeding on baits. Primary repellents invoke instantaneous rejection responses through unpleasant visual, olfactory, taste or irritant cues. Secondary repellents act via an illness-induced learned avoidance and require some ingestion of treated food before learning can occur. I determined the efficacy of several primary repellents (neem oil, agricultural lime and d-pulegone) and a secondary repellent (Avex; an anthraquinone-based product) for deterring a model avian species, the house sparrow (*Passer domesticus*), from feeding, prior to testing the efficacy of the repellents with two native birds: robins and tomtits.

In Chapter 2, I measured the responses of free-ranging house sparrows to wheat treated with primary and secondary repellents over four day periods. Eight sparrow populations were trained to eat plain wheat from food trays on feed tables and were presented, in choice tests, with plain wheat and wheat coated with low, medium or high concentrations of repellent. Wheat treated with either lime or neem oil was consumed by sparrows at the same rate as plain wheat on all days; this suggested that neither compound was an effective sparrow repellent, so I did not evaluate these repellents further. D-pulegone significantly reduced wheat consumption on Day 1, with birds continuing to eat less d-pulegone-treated wheat than plain wheat throughout the four days. Avex did not reduce wheat consumption on Day 1 of exposure, but sparrows ate progressively less Avex-treated wheat over each of the following days. I combined d-pulegone (the primary repellent) and Avex (the

secondary repellent) and compared the efficacy of the combination to the efficacy of Avex alone for preventing feeding. The combination of 2% d-pulegone + 2% Avex reduced wheat consumption significantly more than 2% Avex alone, with the effect lasting over a 10-day test period. The results demonstrated the potential of combined repellents for modifying avian feeding behaviour, and provided evidence for the enhanced efficacy gained by combining primary and secondary repellents.

In Chapter 3, I evaluated the efficacy of the combination of d-pulegone + Avex for deterring native robins from feeding on baits. I identified a preferred dough bait, which I used to offer robins repellent-treated (green and surface coated with a combination of 2% d-pulegone + 2% Avex) and "standard" dough (green and coated with cinnamon oil; the bait formulation currently used for pest control operations in New Zealand). Free-ranging robins were presented baits over four consecutive days on an "arena" of cleared leaf litter, on the forest floor within their home territory. Robins pecked at and removed standard dough more frequently than repellent dough, with the frequency of pecking at repellent dough declining over days. These results demonstrated that the combination of 2% d-pulegone + 2% Avex effectively deterred robins from feeding, but that green dye and cinnamon oil may not be effective deterrents.

As the combination of d-pulegone + Avex had effectively deterred sparrows (Chapter 2) and robins (Chapter 3), I compared this combination with other combinations of repellents and cues in Chapter 4. I presented sparrows with wheat treated with the secondary repellent Avex, paired with either a novel visual cue (blue colour), cinnamon oil (containing primarily olfactory cues), or d-pulegone (containing olfactory, taste and irritant cues). Avex alone significantly reduced wheat consumption, but cinnamon oil + 2% Avex was no more effective than 2% Avex alone. Blue colour + 2% Avex and 2% d-pulegone + 2% Avex elicited the most effective avoidance responses, reducing food consumption by at least 85%, and substantially more than 2% Avex alone or cinnamon oil + 2% Avex. When I compared the combination of blue colour + 2% Avex to colour alone (blue or green), sparrows initially avoided all three treated wheat types. However, sparrows progressively consumed more green and blue wheat each day, eating significantly more of these "colour only" treatments than blue colour + 2% Avex by Day 5. Colour alone did not provide a long-lasting avoidance response. These data clearly demonstrated that combinations of Avex with additional visual or olfactory/taste cues

were effective repellents, but that certain primary cues were more effective than others.

In Chapter 5, I evaluated the efficacy of the blue colour + 2% Avex repellent combination for deterring robins from feeding in comparison to standard baits. Robins pecked at and removed standard baits more frequently than repellent baits, with the frequency of pecking at repellent bait declining over the four days. They pecked more frequently at both bait types in the winter than summer, and juvenile robins tended to peck at repellent bait more frequently than adult males or females. The pecking responses of robins towards both bait types were similar in choice and no-choice tests. The combination of blue colour + 2% Avex effectively deterred most robins from feeding and is likely to reduce their propensity to eat baits during pest control operations.

I compared the feeding behaviour of free-ranging robins and tomtits towards blue colour + 2% Avex baits and standard baits in Chapter 6. Robins pecked at and removed standard baits more frequently than repellent baits, with the pecking frequency for repellent baits remaining very low. Tomtits never pecked at or removed either bait type and they spent less time on the test area than robins. Using an alternative test method in which baits were thrown to birds, robins investigated > 90% of baits thrown to them by an observer, but pecked at significantly fewer repellent baits. Tomtits ignored over 89% of thrown baits. They investigated more standard baits than repellent baits, but never pecked at either bait type. These results clearly indicated a difference in the feeding behaviour of robins and tomtits with respect to the baits, suggesting that tomtits may be less likely than robins to eat bait in some circumstances.

The experiments I conducted in my thesis have demonstrated that combining a secondary repellent with an appropriate primary repellent is a highly effective way of deterring the birds I tested from feeding. Two combinations of repellents (2% d-pulegone + 2% Avex or blue colour + 2% Avex) reduced food consumption more than any single repellent used alone. Not all combinations of cues, however, elicited the same level of repellency and care should be taken to select repellent combinations that effectively deter birds from feeding. I found that a secondary repellent paired with either a novel aversive colour and/or an innately aversive odour or taste reliably repelled birds. For pest control baits in New Zealand, a combination of blue colour and/or d-pulegone + 2% Avex may offer good potential for preventing non-target bird

poisoning. Further research with additional avian species and field testing will now be required to demonstrate the value of these repellents for protecting native birds during normal pest control operations. This additional research should be conducted immediately, so that these findings may be implemented to provide greater protection during pest control to valued native wildlife.

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Tim

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Chapter 1

General Introduction

In this thesis I seek to explore the use of repellents to reduce feeding in birds, in order to determine the potential of repellents for deterring native New Zealand birds from eating baits aimed at killing vertebrate pests. This introductory chapter reviews the background literature associated with the research I conducted. Firstly, I briefly describe mammalian pests in New Zealand, the use of poisonous baits for their control, and the impact of poisons on native bird species. I then discuss strategies for mitigating these impacts, including the potential use of bird repellents. I use the existing literature to describe different types of repellents, methods used to evaluate repellents with avian species and the use of repellents for bird control. I describe the different types of repellent cues and how these relate to avian sensory systems. I then identify promising avenues for repellent research and describe and justify the specific repellents I chose for my research. The chapter closes with a discussion of the bird species chosen for this study, followed by the aims of my research. The structure of the thesis and rationale for the series of experiments I conducted are also described.

New Zealand's pest problem

New Zealand's vertebrate fauna lacked terrestrial mammals, except for three species of bat, until the arrival of the first humans. As such, the indigenous flora, fauna and ecosystems of New Zealand were adapted to living without mammalian species when Polynesian, and later European, immigrants introduced a range of mammals (Holdaway, 1996) for economic, recreational and nostalgic reasons (Clout and Eriksen, 2000). Many of the 31 exotic mammal species present in New Zealand today are now considered to be pests because of the negative impacts they have had on indigenous species, ecosystems or economic practices (New Zealand Conservation Authority, 1999).

New Zealand's introduced mammalian species include carnivorous or scavenging species, such as ferrets (*Mustela furo*), stoats (*M. erminea*), rats (*Rattus rattus, R. norvegicus, R. exulans*) and pigs (*Sus scrofa*), and browsing mammals, such as deer (*Cervus* sp), goats (*Capra hircus*) and brushtail possums (*Trichosurus vulpecula*). Possums are considered one of New Zealand's most significant vertebrate pests (Parliamentary Commissioner for the Environment, 1994), costing the New Zealand economy at least $53 million annually in direct control costs and lost income to farmers from transmitted diseases (New Zealand Conservation Authority, 1999). Brushtail possums were introduced from Australia in the mid-nineteenth century to establish a fur industry (Pracy, 1974), and now occupy more than 90% of New Zealand's land area (Cowan, 1990). In 1994 there were an estimated 70 million possums (Livingstone and Nelson, 1994). As well as browsing on vegetation, possums sometimes prey on native fauna, such as land snails (*Powelliphanta* spp; Sadlier, 2000), and the eggs and chicks of kokako (*Callaeas cinera*; Innes *et al*, 1996) and keruru/kukupa (*Hemiphaga novaeseelandiae*; Pierce and Graham, 1995). Possums also have extensive dietary overlap with some native animals (Cowan, 1990a; Fitzgerald, 1984; Powlesland, 1987), but as yet there is no direct evidence of whether they actually displace native species from these food sources (Sadlier, 2000).

Several introduced mammals, including possums, ferrets, deer, stoats and hedgehogs (*Erinaceus europaeus*) are also known to carry bovine tuberculosis (Tb; *Mycobacterium bovis*; King, 1990). Tb is a problem when it occurs in domestic cattle and deer herds because of the threat it poses to New Zealand's $NZ 5 billion agricultural export trade (Livingstone and Nelson, 1994). The presence of self sustaining pockets of Tb in wild animals, particularly possums, deer (Hickling, 1995) and ferrets (Livingstone, 1996), has been recognised as a potential source of re-infection for domestic herds (Carter, 1995).

Possum management and control

The conservation and disease threats posed by possums and other vertebrate pests in New Zealand have led to extensive efforts to control or eradicate some species. Of all species, possums have engendered the most public debate, research and management (Montague, 2000). Possum control is conducted using a wide range of methods,

including both non-toxic tools and poisonous baits. Methods of possum control that do not rely on the use of poisonous baits include trapping, shooting, chemical repellents and physical barriers (reviewed in Montague and Warburton, 2000). These methods have been developed to meet legislative, environmental, and practical constraints, as well as some people's preference for non-toxic solutions to the possum problem. Non-toxic methods can be extremely successful in some circumstances, and traps and barriers are continually evolving and becoming more effective pest control tools (Montague and Warburton, 2000). Although non-toxic methods are important in the management of possums and other pests, poison-based control, with toxic bait, continues to be the most extensively used technique for controlling possums in New Zealand. The rest of this introduction, therefore, focuses on issues specific to the use of poisonous baits.

Poison-based pest control

Poisonous baits are arguably the most cost-effective means of controlling possum numbers in New Zealand (Morgan and Hickling, 2000). Baits are distributed either aerially, often over very large areas (up to 20 000ha in a single control operation), or laid on the ground or in baits stations by hunters. Six toxicants are currently registered for possum control: 1080 (sodium monofluoroacetate), cyanide, cholecalciferol, phosphorus, brodifacoum, and pindone (Eason *et al*, 2000). The most extensively used toxin is 1080, which is typically incorporated into cereal pellets or applied to carrots for aerial sowing and for use in bait stations. Phosphorus, cyanide, cholecalciferol and 1080 are also used in pastes for ground-based control (Morgan and Hickling, 2000), and cyanide is now manufactured as an encapsulated pellet for ground control (Eason *et al*, 2000). Brodifacoum, pindone, and cholecalciferol are incorporated in cereal baits and only used in bait stations. Cholecalciferol and 1080 are also available in a gel-bait formulation (Eason *et al*, 2000). This selection of toxicants with different properties in a range of different bait types provides those involved in possum control with a selection of 'tools' to use in different circumstances. For example, high-density populations are reduced most effectively by fast-acting poisons, like 1080, cyanide, or cholecalciferol (Henderson *et al*, 1997; Hickling *et al*, 1999; Ross 1999), whereas slower-acting toxicants are chosen for killing possums at low densities or when the total population size is small (Henderson *et al*, 1997). All of the toxins available in New Zealand offer

the opportunity to achieve extremely high kill rates (in excess of 95%) when used correctly (Eason *et al*, 2000; Morgan and Hickling, 2000).

By comparison with other countries, New Zealand uses very large quantities of vertebrate toxins (Eason *et al*, 2000). As our most effective control tool, toxin use is increasing in New Zealand, at a time when toxins are being used less frequently in other parts of the world. Pest control regimes relying so heavily on toxicants are vulnerable to criticism, partly because of the high annual cost (at least $30 million per annum for poison-based possum control alone; Morgan, 1999), but also because of the increased awareness of potential risks of pesticide use worldwide. If overseas markets deemed our pest control techniques to be unacceptable, market access for New Zealand's export agricultural produce could be restricted (Williams, 1994).

Impacts of poison-based control on non-target birds

One of the most significant risks associated with the use of toxicants, is the risk of accidental poisoning of non-target species. Non-target animals include humans, domestic livestock, pets and native wildlife such as birds and invertebrates. In this thesis, I examined ways to reduce feeding by birds on baits, as a way of beginning to address the specific issue of non-target bird poisoning. As I describe below, poison-based possum control has been found to cause some mortality of individuals from several non-target bird species (Spurr, 2000). However, few systematic studies have been published to quantify the extent of poisoning of different species under different pest control regimes. Many reported deaths are attributed to toxic poisoning by implication rather than through testing the dead bird for the presence of toxin. Additionally, few data describe whether poisoning of native birds occurs as a result of bait ingestion by the bird or through some alternative pathway, such as ingestion of pest carcasses containing toxin.

Toxic baits may be distributed to pests by being laid on the ground, placed in bait stations above the ground, or by aerial sowing using helicopters or planes. Each method of bait distribution poses potentially different risks to different native birds. Here, I describe the documented evidence of bird poisoning collected during a wide range of pest control operations using various toxins. The evidence is described according to the methods used to distribute baits.

Ground-laid baits are usually placed on the forest floor on an upturned spit of earth or on a fallen tree branch (Morgan and Hickling, 2000), making them readily accessible to birds that feed at ground level. The toxin cyanide has been found in the bodies of six native and three introduced bird species after ground-laid cyanide has been used, with weka (*Gallirallus australis*) and kiwi (*Apteryx australis*) being most commonly poisoned (Spurr, 2000). Both species feed solely at ground level. As a consequence, the Department of Conservation now requires cyanide baits to be laid above ground where either weka or kiwi are present. After ground-laid 1080 paste was used for possum control, individuals of only four native species (weka, kaka (*Nestor meridionalis*), kea (*Nestor notabilis*) and bellbirds (*Anthornis melanura*)) have been reported to contain toxin. Several other species, including kiwi, kakariki (*Cyanoramphus* spp.), keruru, pukeko (*Porphyrio porphyrio*), robins (*Petroica australis*) and saddlebacks (*Philesturnus carunculatus*), have been observed eating 1080 paste baits in palatability trials (Morgan, 1999).

Toxic baits used in baits stations also pose some risk to non-target birds. Weka, robins and house sparrows (*Passer domesticus*) have been observed to eat cereal baits directly out of bait stations (Spurr, 2000). Pests sometimes spill bait from stations as they feed, where the baits become readily accessible to a variety of birds. Robins have been found dead after being seen to eat cereal-based baits containing brodifacoum that were removed from the bait stations by rats (Eason and Spurr, 1995). It is generally assumed that bait in bait stations poses less risk to birds than ground-laid baits (Spurr, 2000), but no studies have attempted to quantify or compare the number or proportion of individuals of any native bird species that have been poisoned during bait station- or ground-based control of pests.

Most research on the impact of poisoning on non-target birds has been directed at the use of aerially sown 1080 baits. More individuals from a wider range of native bird species have been reported to contain toxin after aerial 1080 operations than after control using baits that are ground-laid or used in bait stations (Spurr, 2000). While this may indicate that aerial 1080 poisoning poses a greater risk to birds, it may also be an artefact of greater sampling effort allowing greater detection of poisoning. Therefore, apparent differences in impact on non-target birds between different toxins or bait distribution methods should be interpreted with caution, at least until systematic comparative studies are conducted. Individuals of 19 native and 13 introduced bird species have been found

dead (and to contain toxin) after carrot- or cereal-based operations. Ground feeding birds, such as blackbirds (*Turdus merula*), chaffinches (*Fringilla coelebs*), tomtits (*Petroica macrocephala*) and robins are particularly vulnerable to poisoning (Brown, 1997; Empson and Miskelly, 1999; Harrison, 1978; Powlesland *et al*, 1999). Other insectivorous forest birds like whiteheads (*Mohoua albicilla*), grey warblers (*Gerygone igata*), riflemen (*Acanthisitta chloris*), fantails (*Rhipidura fuliginosa*) and silvereyes (*Zosterops lateralis*) have also been found dead (Harrison, 1978).

The data available on non-target bird poisoning does not clearly identify how native birds ingest toxin. However, recorded observations of some birds eating baits suggest that at least some species of native birds are poisoned by eating baits directly. In the following two sections I look in more depth at the potential pathways of native bird poisoning and then at whether poisoning of some individual birds may be acceptable if these deaths do not lead to overall declines in native bird populations.

Pathways for non-target bird poisoning

Non-target birds may be poisoned by primary or secondary poisoning. Primary poisoning occurs when a bird eats sufficient quantities of a toxic bait to be killed. Secondary poisoning occurs when a bird eats sufficient quantities of another animal that has fed on toxic bait (e.g. invertebrates or pest mammals that have eaten bait) to be lethally poisoned. For many birds, the actual pathway by which individuals die during a control operation is unknown, and the quality of data available to determine poisoning pathways is poor. It is assumed that most birds die from primary poisoning (Spurr, 2000) but there is only limited evidence that supports bird poisoning via this route. Whiteheads and robins have been observed eating baits (Spurr, 1979; Spurr and Powlesland, 1997), and carrot baits have been found in the gizzards of blackbirds and chaffinches (Spurr, 2000). Insectivorous birds found dead during control operations (with toxin residues present in muscle or liver tissue) have usually had empty gizzards (e.g. tomtits; Powlesland *et al*, 2000), and it has been suggested these species may regurgitate poisoned bait before dying. Alternatively, these birds could equally have eaten and regurgitated invertebrates that had fed on baits. Predatory and scavenging birds (e.g. morepork, *Ninox novaeseelandiae*) that have been found dead after 1080 poisoning operations are thought to have died from consuming dead or sub-lethally

poisoned possums, rodents, invertebrates or small birds (Spurr, 2000). Innes and Barker (1999) used food webs to describe the potential pathways that various toxins could move around ecosystems. For aerially distributed 1080, there are many potential pathways by which birds could be poisoned. For example, an insectivorous bird could theoretically be poisoned after eating maggots (*Lucilia* spp., blowfly larvae) that had ingested toxin when feeding on the carcass of a possum that had eaten a lethal quantity of bait. Unfortunately, very few of the potential pathways for non-target poisoning have been scientifically demonstrated, because the research is difficult and has never been attempted (Innes and Barker, 1999).

For most native animals toxicological data on bait consumption and poisoning is limited or non-existent, as experimental poisoning to determine lethal dose (LD) values cannot be justified on ethical grounds. However it would seem, in theory at least, that many of New Zealand's native birds would need to eat very little bait or other toxic material to be lethally poisoned. Some estimates of LD values have been made from data collected in similar species. Lloyd and McQueen (2000) estimated LD_{50} values for native birds exposed to 1080, based on data collected from 31 other Australasian passerine species. From this data, poisoning thresholds for native birds exposed to 1080 baits, at two concentrations that are typically used during poisoning operations (0.08% and 0.15% wt/wt) were determined. These calculations suggest that small forest birds such as robins and tomtits need only to consume between 0.05g and 0.30g of bait to ingest an LD_{50} quantity of toxin (Lloyd and McQueen, 2000). This represents between 0.6% and 1.5% of the daily food intake of either species. The weight of food fragments consumed by small birds each time they peck has not previously been reported, but it is likely that most small birds would be at risk of lethal poisoning from only a few pecks at baits. In this thesis, I focus on strategies for minimising the direct consumption of bait by birds, and do not focus on the issue of secondary bird poisoning. Further research will be required to address the extent and impact of secondary poisoning on bird populations.

Is some level of non-target poisoning acceptable?

It is possible that some level of poisoning in a bird population is acceptable, at least for the viability of the population as a whole (Parliamentary Commissioner for the

Environment, 1994). It has generally been assumed that the benefits of possum control outweigh the risks to non-target species (Spurr, 1991), but there is only limited evidence (because few controlled studies have been conducted) to support this (Spurr, 2000). Benefits may occur when the immediate loss of individuals at the time of a control operation is offset by the subsequent recovery of the population after removal of possums and rodents. For example, one year after an aerial 1080 operation in Pureora Forest that killed 55% of monitored robins, the population size and nesting success were greater than they had been pre-control (Powlesland *et al*, 1999). The increase in population size and breeding success were attributed to the reduction in possum and rodent numbers, both of which prey on birds' eggs and chicks. Further research with robins and other species, such as tomtits, is being conducted to evaluate the consistency of this finding (e.g. Westbrooke *et al*, in prep.).

Despite the loss of some individuals, Spurr (2000) argues that there is little evidence of deleterious long-term impact of poisoning for possum control on non-target bird species that have been adequately monitored. I suggest that there is good evidence of deleterious impact for some bird species, but many species have not been monitored adequately enough to determine the impacts or benefits (Veltman, 2000) of pest control. Weka populations have been reduced by 80-100% in some instances (Eason and Spurr, 1995), and these loses are seen by many to be unacceptable. As a result, weka (and other vulnerable species) have sometimes been taken into captivity during aerial poisoning operations (e.g. during the Kapiti Island and Mokoia Island rodent eradications; Spurr, 2000). Removal of native birds from areas to be controlled is logistically difficult, expensive and risky to the health of the birds (e.g. Owen, 1998). Therefore, strategies to make poisonous baits bird-safe are highly desirable.

In this thesis I take the following philosophy. Anything that can be done to cost-effectively reduce the risk of poisoning non-target birds during control operations will be beneficial to the pest control industry, and should be investigated. The benefit may arise from reduced risk of accidental poisoning, or equally, may arise from better public perception of New Zealand's poisoning methods. The risk of non-target mortality (either real or perceived) is a significant factor influencing the acceptability to the public of possum control techniques (Fitzgerald *et al*, 2000). In the following section, I describe strategies that may be used to help prevent non-target poisoning.

Mitigating the impact of poison-based pest control on non-target birds

The risk of primary poisoning posed by poisonous baits to non-target animals has been expressed by Morgan (1999) as:

$$Risk = Hazard \times Exposure$$

The hazard is determined by the susceptibility of the non-target species to the toxin delivered in the bait. The exposure is determined by the availability of the baits and the acceptability of the baits to non-target animals. In the sections below, I describe current and potential methods for reducing hazard and exposure.

Reducing hazard

The toxicity, persistence and mode of action of different toxicants will determine the hazard to non-target birds (Eason *et al*, 2000). All of the toxicants used for possum control in New Zealand may cause death to non-target birds if they choose to eat baits. However, some toxicants pose a greater hazard than others. For example, brodifacoum may be more hazardous than other toxins such as cholecalciferol to some non-target species, because of its accumulation in animals over time and toxicity to a wide range of species; there is some evidence that individuals of many native species will be exposed to brodifacoum after poisoning operations (Eason *et al*, 2000). Cholecalciferol, on the other hand, may be less hazardous to non-target species, because concentrations used (and toxic to possums) are low compared to doses that are toxic to some non-target species (Eason *et al*, 2000). Reports of non-target deaths resulting from ingestion of cholecalciferol baits are rare (Spurr, 2000). However, cholecalciferol is not used as widely as other toxins, so avian impact may not have been recorded or noticed. Recently, the Department of Conservation in New Zealand has restricted the use of brodifacoum baits on publicly-owned land (Eason *et al*, 2002). In future, it is likely that stricter controls will be placed on when and where brodifacoum-based baits can be distributed, with the hope of reducing hazard to non-target species. Further research will be required to demonstrate whether using alternative toxins does, in fact, reduce hazard.

Reducing Exposure

Exposure to bait is determined by: (1) the availability of the baits; and (2) the acceptability of baits to non-target birds.

(1)   Availability of baits

The availability of poisonous baits to non-target birds depends on the type, intensity and frequency of control operations. Aerial poisoning operations distribute bait over large areas, making bait potentially available to many non-target birds in all parts of the control area. I have described the recorded impacts of aerial poisoning on birds earlier in this chapter. Bait stations provide large quantities of bait at localised sources, although access is restricted to the baits for many birds. Both methods of bait distribution pose a risk of poisoning to non-target birds (as described above).

Bait sowing rates can now be reduced to around 2kg/ha (compared to previous sowing densities of up to 20kg/ha) without affecting the efficacy of possum control (Morgan, 1999). This reduces the availability of toxic baits to all animals and may reduce the frequency of bird-bait encounters (Spurr, 2000), although no data have been collected to demonstrate this. Researchers are currently attempting to determine the effect of bait sowing rate on poisoning of one vulnerable bird species, the tomtit (Westbrooke et al, in prep.). Minimising the frequency and intensity of maintenance operations and careful management of the timing of possum control in relation to breeding of non-target species (e.g. not poisoning populations when newly fledged birds that may eat baits are present) may further reduce negative impacts (Morgan, 1999).

Using target-specific bait delivery may also reduce the availability of toxins. McDonald *et al* (1999) have developed a possum-specific mechanical bait dispenser, which possum readily operate but birds do not (Day and Matthews, 1998). If the efficacy and cost-effectiveness of such devices can be demonstrated, they may become valuable tools for safely delivering poison to possums.

Another method for reducing the availability of toxic baits to non-target species is to exclude possums (and other pests) from areas that contain the non-target animals. Pest exclusion has the advantage of reducing the need for on-going control, thereby reducing the direct impact of control operations on non-targets. It has the additional

benefit that non-target species do not have to compete with, or become prey to, remaining pests after the operations. The best examples of pest exclusion are found on the offshore islands (e.g. Kapiti Island), where pest eradication has played a significant role in the protection of New Zealand's non-target and highly valued native animals and plants (Atkinson, 2001). The recent development of effective pest-proof fence designs (e.g. Day *et al,* 2000; Day and MacGibbon, 2002) may allow for similar exclusion and reduced reliance on toxic baits on mainland New Zealand.

Methods for reducing bait availability to birds have only been developed recently. No research has been published to date that actually quantifies whether any of the methods I have described above actually reduce risk to non-target animals. For example, lowering the sowing rate or using exclusion fencing will decrease the number of baits in a given area over time, but may not reduce poisoning of ground feeding birds. Weka could still find and eat sufficient toxic bait to be killed on the day the poison was distributed, so the impact would still be the same. They could also be poisoned via secondary routes (e.g. scavenging possum carcasses), and this type of poisoning may not be dependent on bait density. Further, many pest control operations are now conducted in areas which already have lowered pest densities from previous control work, and so the number of baits available to non-target birds (i.e. baits that are not eaten by pests) may remain relatively high. I believe that further experimental studies are required to determine whether reduced applications rates, or tools that make baits harder to access, will benefit any non-target bird species in terms of reduced poisoning risk.

(2)   Acceptability of baits

Another way to reduce the exposure of non-target species to bait is to reduce bait acceptability. The acceptability of baits to non-target birds is influenced by a number of physico-chemical properties of the material that influence feeding behaviour, including: (a) bait type; (b) bait size; (c) bait colour; and (d) other bait additives. In the next four sections, I describe each of these bait characteristics and how they may be used or manipulated to reduce bait acceptability to birds.

(a)   *Bait type*

Some non-target birds eat existing cereal, carrot or paste bait formulations, but different baits may be more or less acceptable to different species. Little is known about which bait types are more readily eaten and therefore pose more risk to each species, but it is likely that all current baits pose some risk to some species. Significantly more birds are found dead after operations using carrot baits than after operations using cereal-based baits (Spurr, 1994). For example, tomtit mortality appears to be highest during carrot operations, and low or nil during cereal operations (Powlesland *et al*, 2000; Westbrooke *et al*, in prep.), but other factors that may have affected mortality were uncontrolled in these studies. Carrot-based control operations generally use higher bait application rates than cereal operations, so it is yet to be determined whether tomtit mortality is related to sowing rate or bait type. Bait type may influence feeding intensity by other species that feed on baits, including the invertebrate prey of avian species. For example, Spurr and Drew (1999) found in one study that ants (*Huberia brouni*) and weta (e.g. *Gymnoplectron* spp.) fed most frequently on cereal baits, while earwigs (*Parisolabis* spp.) and weevils (of the *Curculionidae* family) were found feeding predominately on carrot bait. This could lead to a differential risk of secondary poisoning for birds, depending on the bait type used and feeding behaviour of the bird. Alternative bait types continue to be developed, both to improve the efficacy of possum control and to reduce non-target acceptability. Recently a gel bait has been developed (marketed by Kiwicare Ltd, Christchurch) that appears to be low in acceptability to a wide range of non-target animals including birds and invertebrates (Morgan, 1999). Morgan's (1999) results demonstrated that in experimental situations many native species did not feed on any gel bait, but the efficacy of this bait for preventing poisoning during control operations has not been determined. This and other new bait types may become increasingly useful for minimising non-target impact, but much more research will be required to determine if they reduce bird impact without compromising acceptance by pests.

(b)   *Bait size*

Few studies have systematically determined what size of bait can be manipulated and eaten by a range of New Zealand's native birds. Spurr (1993) conducted experiments with large native birds such as weka, kaka, kakariki, kokako and saddleback and found that when offered a choice between baits of different sizes, they preferred larger baits (2-6g) over small baits (<2g). Spurr reported that the birds preferred the bigger baits because they could easily hold these in their claws while they ate them, but that the birds ate all bait sizes eventually. In replicated field trials using 1080 baits, Harrison (1978) showed that fewer small forest birds were killed when small baits had been sieved out. From these results, Harrison (1978) suggested that small forest birds can easily manipulate and eat small bait fragments, but do not eat larger baits. However, the results could also be interpreted as showing that fewer birds were killed when fewer baits were applied, as bait weight, but not bait number, was controlled.

  In aerial 1080-poisoning operations, most recorded bird deaths occurred before 1977 and were attributed to the use of unscreened, poor quality carrot bait containing a lot of very small pieces ("chaff") (Harrison, 1978). While many deaths were recorded, systematic data were not collected prior to 1977 to determine the full extent of the bird impact. In more systematic monitoring, few birds have been reported dead after aerial 1080-poisoning operations since 1977 (Spurr, 1994; Spurr and Powlesland, 1997), when small bait fragments were banned: the Pesticides Act (1979) requires that all baits be larger than 16mm in size. For example, 83 birds (including 34 native) were found dead after 70 aerial 1080-poisoning operations using screened carrots or cereal-based baits from 1978 to 1993 (Spurr, 1994). However, many other changes have occurred to poisoning operations during this time period (e.g. quality control has been improved for toxin content in baits, sowing rates have been lowered; Morgan, 1999), so the reported reduction in recorded deaths (Spurr, 2000) cannot be attributed solely to removal of bait fragments. There is a general perception in the pest control industry that using large baits has saved and will continue to save many non-target birds from accidental poisoning (Spurr, 2000). The evidence suggests that there remains a risk to birds from toxic baits and that to reduce this risk, further research is needed to develop procedures to reduce

contact by birds with baits. I record how native birds interact with baits in my thesis, but I do not conduct any studies to specifically address the issue of bait size.

(c)   *Bait colour*

Following deaths of native birds in rabbit control operations in the early 1950s, bait colour trials, using domestic chickens (*Gallus domesticus*), were initiated by Caithness and Williams (1971) to determine whether specific colours could be used to deter birds from poisonous baits. Caithness and Williams (1971) examined colour preferences in a single group of chickens, and found that the chickens ate less green-dyed grain than yellow or blue grain when it was offered in choice tests on the grass. They then tested the preferences for plain or green-dyed grain with mixed flocks of wild sparrows, wild California quail (*Callipepla california*) and wild finches (species not specified). They found that the flocks consistently ate more plain grain than green-dyed grain. Caithness and Williams (1971) concluded that dyeing grain discouraged birds from eating it and that green was the most effective colour to use. Further work with one native species, the weka (method was not adequately described), concluded that weka preferred yellow over red and red over green foods (described in Udy and Pracy, 1981), although Udy and Pracy (1981) noted that weka were later observed eating green-dyed pellets in poisoning operations. As a result of these limited experiments, the New Zealand Pesticides Act (1979) was written to require that all possum baits must be dyed green.

   Since it has been mandatory for all baits to be dyed green, several bird species have been recorded to eat baits during pest control operations (Spurr, 2000). However, records of birds eating baits are sporadic and usually anecdotal, rather than part of a systematic study. Therefore, the effect of the colouring the baits green on bait consumption during pest control operations has not been fully quantified for any species. Recently, Hartley *et al* (1999, 2000) conducted colour preference studies with two native birds (robins and weka) and found that when given a choice between red, yellow, brown, green

and blue foods, weka and robin least preferred blue. This contrasts to Caithness and Williams' (1971) finding that green was less preferred than blue. Insufficient methodological detail is given for Caithness and Williams' research to determine if methodological factors may have contributed to this difference. Hartley *et al*'s (1999, 2000) choice test methods, where all colours were presented at the same time, enabled a direct comparison of the relative preference of the birds for each bait colour over time. These studies provided a strong indication that robins and weka find blue-coloured food less preferable than other colours, but the research did not investigate whether birds would avoid blue baits in a pest control operation. Possums readily eat lethal doses of blue-coloured bait (Day and Matthews, 1999), so adding a lowly preferred colour to bait could be an inexpensive way to help reduce the number of birds that are poisoned. However, Hartley *et al* (1999, 2000) found that blue colour alone was not avoided for very long (e.g. within four days weka consumed over 70% of blue food offered per day) and thus may not be a reliable deterrent in poisoning operations. I suggest that the use of a lowly preferred colour in bait has significant potential for reducing the acceptability of bait to birds, and should be explored further. Additional methods or additives (such as odour or taste repellents) that enhance or prolong the negative effect of such colours on food consumption are needed and I explore this avenue of research further in my thesis.

(d)   *Bait additives*

As mentioned above, an obvious approach to reducing bait acceptability would be to extend the colour approach by using other additives (such as odour or taste repellents) that deter birds without compromising bait acceptance by pests. In New Zealand, the first research into bird repellents for pest control baits was the colour preference work described above. Following the realisation that colour alone would be insufficient to promote long-lasting avoidance of baits, Pracy *et al* (1982) optimistically sought to identify if possum attractants could also act as avian repellents. Over 40 food flavours were offered in choice tests to free-ranging birds at several sites on Kapiti

Island. Baits were treated with the flavours and placed on the ground where any bird could access the baits. Only weka showed any interest in the test sites and baits. A number of flavours significantly reduced bait consumption by weka, but none entirely prevented weka from feeding. Baits treated with several of the "lures" were also readily eaten by possums: almond, bayleaf, clove, cinnamon, eucalyptus, lemon, peppermint, bergamot, gingerine, nutmeg, pimento leaf and spearmint.

Of the flavours listed, only cinnamon oil was tested further for bird repellent effects. Kaka and mallard ducks (*Anas platyrhynchos*) were offered familiar foods coated with cinnamon oil for one day and both species completely avoided the cinnamon flavoured test food (Udy and Pracy, 1981). However, as the cinnamon-treated familiar foods were only offered for one day, this rejection may have simply reflected neophobia. Neophobia is a fear of novel stimuli and in the context of feeding behaviour may act to prevent animals from feeding on food containing novel cues at first exposure. Animals usually habituate to these novel components in the food (e.g. weka habituated to novel colours in baits within 2 to 4 days; Hartley, 1999), in much the same way as they may habituate to a weak repellent. If the birds had been offered the cinnamon baits for more than one day, they may have eaten them.

Despite Udy and Pracy's (1981) study being the only evidence that cinnamon oil deters birds (for one day in a choice test), cinnamon has been routinely incorporated into carrot and cereal baits in New Zealand since 1983 (Spurr and Powlesland, 1997). Cinnamon is added partly to mask the smell and taste of 1080 from possums (Morgan, 1990) and partly to repel birds during control operations (Spurr, 1993). Neither function can be substantiated based on data that has been published. The effectiveness of cinnamon oil as a bird repellent has since been further examined on a handful of captive native bird species with mixed results. Spurr (1993) found that some captive individuals of native species (weka, kaka, kakariki, kokako, and saddleback) were only deterred for a day, and most not at all, by cinnamon when it was offered in choice tests each day. The same baits were used throughout the study, so the cinnamon may have degraded over time, reducing its potential for repellency. Hickling (1997) found the deterrent effect of cinnamon baits

relative to plain baits increased for kaka with repeated exposures when the cinnamon oil was fresh each day. McLennan *et al* (1992) found that captive kiwi were undeterred from feeding when their regular food was treated with cinnamon.

Several other repellents have been tested for use in baits in New Zealand, but few have been tested with native birds. Methyl anthranilate, for example, at a concentration known to repel house sparrows (2.5%) also deterred rats (Spurr *et al*, 2001), so was never tested for repellency to native birds. Cinnamamide has recently been found to deter weka and kea from eating baits without affecting bait acceptance by possums (Spurr and Porter, 1998). However, bait acceptance by rats was reduced and the compound is relatively expensive. Other repellents that have been considered for use in baits include dimethyl anthranilate, ortho-aminoacetophenone, tannic acid (Spurr and Porter, 1998; Spurr *et al*, 2001), amyl acetate and Optamint oil (McLennan *et al*, 1992). While many of these repellents were found to reduce the food consumption of birds in studies overseas, each of these repellents were rejected for use in pest control baits because they were either too costly or had deleterious effects on bait consumption by target pests (Spurr and Porter, 1998; Spurr, *et al*, 2001). As such, they have not been tested for their effects on New Zealand bird species. Thus, cost-effective avian feeding repellents that do not deter pests are still required and this is the focus of my research.

Repellents

In this part of my introduction, I explore repellents to a much greater depth. Firstly, I describe what repellents are and why and where they may be used for the management of bird behaviour. I discuss the modes of action of repellents and the types of repellents that are available. I also discuss how these repellent cues relate to avian sensory systems. From these descriptions, I highlight the most promising avenues for identifying avian repellents for use in pest control baits and critique the methods used to evaluate repellent efficacy with avian species. I then outline the rationale for the repellents and bird species I chose to study in this thesis.

What are repellents?

Repellents are substances or sensory cues that act directly on animals to modify their behaviour to prevent them from interacting with a treated object, area or food. In the context of feeding behaviour, repellents directly reduce the consumption of a treated food (either partially or completely), but are not lethal at the concentrations used (Mason and Clark, 1997). Many naturally occurring and man-made lethal substances will also prevent animals from feeding if they consume a sub-lethal quantity, but if they cause lethal poisoning, they are described as toxicants (Mason and Clark, 1997).

Why and where repellents may be used for bird management

Land-use and cultural changes around the world over the past few decades have led to dramatic increases in populations of some avian species. For example, North American Canada goose (*Branta canadensis*) populations are now 20 times larger than 40 years ago (Ankney, 1996), and this species is now being controlled as a bird pest in parts of New Zealand (Hughes and Ottmann, 1996). Increases in numbers of nuisance birds have resulted in frequent bird-human conflicts in agricultural, recreational (e.g. parks, golf courses), and airport settings (Cleary *et al*, 1997; Covoner and Chasko, 1985; Kahl and Samson, 1984). These conflicts include economic loss to crops, physical damage to buildings and structures, and health and safety concerns near urban areas (Dolbeer *et al*, 1998). Most bird management issues arise because birds try to consume food resources or use roosting sites that humans do not want them to. Food resources may include grass or plants around work or recreational areas, planted crops or stored feed (Mason and Clark, 1997). As such, methods to modify the behaviour of birds are required.

  Large scale lethal management of nuisance birds, such as shooting or poisoning, is often inconsistent with social ethics or is impractical (Dolbeer, 1986, 1998). Numerous non-lethal frightening and exclusion devices have been used in efforts to prevent bird damage, but many are also ineffective or cost-prohibitive (Dolbeer *et al*, 1995). Effective non-lethal techniques to manage birds are highly desired, so a significant body of research has focused on identifying cues or repellents that could, in particular, be used to modify the feeding behaviour of birds (see reviews in Mason, 1997). Despite this research, very few repellents are actually available for bird control. For example, of 43 bird damage control agents registered in the United

States, only seven are repellents, and most do not prevent damage (Mason and Clark, 1997).

In addition to nuisance birds, many other avian species are negatively affected by the activities of humans. People routinely use pesticides to control invertebrate and vertebrate pests, and birds may be accidentally exposed to these toxicants. For example, in New Zealand, vertebrate pest control is conducted over large areas for conservation goals and to prevent the spread of Tb to cattle and deer (see Montague, 2000). The baits that are used to conduct the pest control expose native birds to the risk of accidental poisoning (Spurr, 2000). A similar poisoning risk occurs for native birds in the United States, where pelleted agricultural chemicals are used on crops (Mason and Clark, 1997). Obviously it is not desirable to kill native birds, so repellents have been proposed as one way of decreasing this risk.

Modes of action and characteristics of repellents

Repellents are described as having either: (1) primary; or (2) secondary modes of action (Rogers, 1978).

(1)   Primary repellents

Primary repellents require little or no learning to be effective, as animals immediately reject foods treated with the repellent because of unpalatable cues presented by the substance (Clark, 1998). These cues may be visual, olfactory, gustatory (taste), tactile or chemesthetic (irritant) in nature, and I describe each type of repellent cue in relation to avian senses in the next section. These cues are usually highly conspicuous to the receiver (e.g. highly volatile odours, such as d-pulegone; Wager-Page and Mason, 1996). While primary repellents provide sufficiently strong stimuli to disrupt short-term feeding behaviour, their unpalatability is not of sufficient strength or relevancy to cause post-ingestional distress or promote learned avoidance (Domjan, 1998). Animals frequently habituate to the noxious stimuli presented in a primary repellent (Clark, 1998). For example, a bird presented with food containing aversive olfactory cues may initially avoid it. However, if the bird consumes a small quantity of the food and suffers no further negative experience

after eating, it may begin to eat more. Over several exposures to the food, in which no negative feedback results, the noxious olfactory stimuli may be ignored.

In practice, primary repellents are often derived from natural products used as human food and flavour ingredients. These chemicals have few toxic biological effects on the target species and favourable environmental degradation characteristics (Sayre and Clark, 2001). As such, the use of primary repellents has often been promoted as filling the need for effective, environmentally safe and non-harmful repellents (Mason and Clark, 1992). Despite these positive attributes, primary repellents have not achieved a high level of success when used in the field (Sayre and Clark, 2001). The strong cues frequently associated with primary repellents tend to degrade once exposed to environmental conditions (Aronov and Clark, 1996). When the primary repellent is removed or degraded, targeted animals typically return to feed because the repellent has not had any long-term negative effect on the animal (Covenor, 1984; Glahn et al., 1989) or does not induce a long lasting avoidance response. In the context of deterring birds from eating pest control baits, primary repellents pose a risk of poisoning to any bird that habituates to the effects of the primary repellent and begins to eat bait while it is still toxic.

(2)   Secondary repellents

Secondary repellents act via an illness-induced learned avoidance response, which requires ingestion of some treated food before learning can occur (Clark, 1998). The avoidance response is learned by a process of classical conditioning (Pavlov, 1906) that depends on 4 critical features: (1) an unpleasant experience (i.e. the unconditioned response (UCR), which is usually illness) attributed to (2) the substance which causes the unpleasant experience (i.e. repellent (the unconditioned stimulus (UCS)); (3) the sensory cues associated with the repellent (the conditioned stimulus (CS)); and (4) the avoidance of those conditioned cues (the conditioned response (CR)) (Sayre and Clark, 2001). The strength of the avoidance (CR) is usually positively related to the magnitude of illness (UCR) caused by the repellent (UCS) (Domjan, 1998). The degree of illness is related positively to repellent concentration (e.g. rodents; Nacham and Ashe, 1973), so increasing concentration (e.g. secondary repellent concentration) may increase the UCR.

The rate of learning and strength of avoidance caused by secondary repellents may be enhanced by ensuring that highly salient ancillary cues (CS) are associated with the repellent (Sayre and Clark, 2001). When used alone, the only conditioned stimuli provided by a secondary repellent are the taste, odour, visual, irritant or other cues provided by the repellent chemical and the food it is presented on. In many cases, secondary repellents do not have particularly strong CS (visual, odour, taste, tactile or irritant stimuli) associated with them (Clark, 1998). Kalat and Rozin (1971) defined stimuli salience as the likelihood that a CS will be associated with illness. Salience of the CS to the receiving animal has been demonstrated to be dependent on novelty for rats and lambs (Kalat, 1974; Provenza *et al*, 1993, 1995). A salient CS may enhance the development of an avoidance response if the UCS has weakly detected stimuli associated with it (Reidinger, 1997). This occurs because the CS provides additional cues that are avoided along with any cues present in the UCS (repellent). As such, combining secondary repellents with other salient stimuli which are able to be associated with the UCR may be more effective at deterring birds than less salient stimuli, because the birds will have better conditioned stimuli with which to develop an avoidance response (Sayre and Clark, 2001).

Several examples of using salient CS to enhance the effects of secondary repellents on avian species exist. Methiocarb (a secondary repellent) causes severe reversible illness after ingestion and several bird species readily learn to avoid a novel colour, pattern, odour or taste that is associated with the illness (Conover, 1984; Garcia et al, 1966; Mason and Reidinger, 1983; Tobin, 1985). After accounting for novelty effects, methiocarb reduces food consumption more when it is paired with a visual cue like red colour than when presented alone (Mason and Reidinger, 1983; Nelms and Avery, 1997). However, ancillary cues do not always lead to enhancement of the response. Multi-stimuli combinations of cues (e.g. visual, olfactory and taste cues all presented together) can be more effective that one cue or CS presented alone (see Rowe, 1999 for a review of this topic), but these cues can also overshadow (Kalat and Rozin, 1973) or block each other, due to concurrent interference and paired relevance (Sayre and Clark, 2001).

In practice, secondary repellents are usually highly effective for preventing birds from feeding (Sayre and Clark, 2001). They are often chemicals derived from synthetic agricultural pesticides (e.g. methiocarb; Fagerstone and Schafer, 1998) and as a

consequence, they often have undesirable physiological or metabolic side effects. This means they are often perceived as being less safe for animal use than primary repellents (Sayre and Clark, 2001), so methods to minimise the concentrations of secondary repellent required are desirable (e.g. through the use of additional sensory stimuli; Nelms and Avery, 1997). In the context of deterring birds from eating pest control baits, accidental poisoning will arise if the UCR caused by the secondary repellent does not produce a conditioned avoidance response (CR) before the bird has consumed a lethal quantity of the pesticide. Therefore, methods that reduce the amount of food consumption required for a repellent effect may help to prevent accidental poisoning. In the following section, I explore the types of sensory cues that may be effective as repellents or CS in relation to avian sensory systems.

Types of repellent cues and avian senses

Any primary or secondary repellent contains one or more sensory cues that birds must respond to for the repellent to be effective. In animal communication systems, the most effective cues or stimuli are usually those which have high detectability, discriminability and memorability for the target animal (Guilford and Dawkins, 1991). Cue detection is determined largely by the sensory abilities of the receiver, so appropriate stimuli that target the most responsive senses will be most effective. For example, it would be pointless to present an ultrasonic sound to some bird species, because they may not detect such frequencies (Avery, 1997), but red-, yellow-, green- or blue-coloured foods would be readily detected, as avian colour vision is highly developed (Varela *et al*, 1993).

Discriminability refers to an animal's ability to recognise that a cue belongs to a discreet category (Guilford and Dawkins, 1991). Effective repellents require animals to discriminate between cues in palatable food and cues in the unpalatable repellent-treated food. For birds, there is good experimental evidence from captive animals that discriminability is enhanced by the addition of prominent visual or olfactory cues (Bullard et al, 1983).

Memorability of cues is important where learning is involved (Guilford and Dawkins, 1991), such as for secondary repellents. Birds must learn to avoid a CS and then remember the association in future encounters. Many factors affect an animal's

ability to remember associations, including the intensity of the UCR, the consistency of the association and the animal's prior experience with the cue (Avery, 1997; Guilford and Dawkins, 1991). Cues with high contrast (cues that stand out from the background on which they are presented) enable faster learning and better memorability (Gittleman and Harvey, 1980; Roper and Redston, 1987). Novelty is also an important factor in memorability, with previous exposure limiting the potential for any cue to enhance avoidance learning (Mason and Reidinger, 1983). For example, possums show learned avoidance of novel baits after sub-lethal poisoning (O'Connor and Matthews, 1999), but do not learn to avoid baits if they have been pre-exposed to them (Moss *et al*, 1999). This suggests that novel cues will offer much more potential for enhancing bird repellent efficacy than familiar cues.

The following sections describe the primary cues used by birds in making feeding decisions and how repellents or conditioned stimuli that target these senses may be used to enhance repellency.

(1)   Visual cues

The colour vision of birds is arguably their most highly developed sense, being more elaborate than that found in many vertebrate species (Varela *et al*, 1993). A bird's colour vision differs from a human's in several ways. Birds have at least four, or frequently five, classes of cones in comparison to the three in humans (Bowmaker *et al*, 1997). In addition, the maximal sensitivity of each type of cone falls at different wavelengths across the electromagnetic spectrum. Many, if not all, diurnal birds have a cone in, or close to, the near ultraviolet region of the electromagnetic spectrum (Bennett and Cuthill, 1993; Chen *et al*, 1984; Finger and Burkhardt, 1994). Humans, in contrast, are not visually sensitive to ultraviolet light (Thompson *et al*, 1992). Individual bird species may have features of their vision adapted to specific visual tasks, but little is known about differences between species with respect to different ecological niches or feeding behaviour (Varela *et al*, 1993). Further understanding of these differences may be critical for designing repellents that are effective for specific target species.

In most bird species, including diurnal passerines, vision is the primary cue used for making feeding decisions (Avery, 1997; Avery and Nelms, 1990; Gillette *et al*, 1983). Birds use colour to select preferred food and avoid toxic, unpalatable, or

unprofitable food (Mastrota and Mench, 1995a). Birds demonstrate colour preferences, both in flocking situations (e.g. Brunner and Coman, 1983; Caithness and Williams, 1971) and when individual birds are presented colour choices (e.g. Hartley *et al*, 1999, 2000; Mastrota and Mench, 1995a). However, most studies with individual birds have commented on the variability in colour preferences between individuals (Puckey *et al*, 1996; Willson and Comet, 1993; Willson *et al*, 1990). In contrast, the feeding behaviour of flocking birds is often affected by the choices of their flock mates, so individual colour preferences can be hidden (Reidinger and Mason, 1983; Ward and Zahavi, 1973).

Birds rapidly habituate to lowly preferred or avoided novel colours if they are presented alone (e.g. Hartley, 1999; Mastrota and Mench, 1994). This rapid habituation, if there are no negative consequences from eating the novel coloured food, limits the usefulness of colour alone as a repellent (Mastrota and Mench, 1994). However, because birds rely so heavily on visual cues when making feeding choices, visual cues may be ideal conditioned stimuli for other bird repellents. Several researchers have found that addition of a visual cue enhances the speed and persistence of avoidance learning by birds towards repellents (Greig-Smith, 1987; Greig-Smith and Rowney, 1987). The most robust avoidance responses conditioned by secondary repellents appear to be developed when a novel colour is the primary CS (e.g. Avery and Mason, 1997; Nelms and Avery, 1997).

There have been a few, contradictory, studies evaluating which colours are better than others for conditioning avoidance towards repellents. Some have found that bright, preferred (or perhaps lowly preferred but conspicuous aposematic) colours may provide the best visual cues (e.g. Mason *et al*, 1993; Mastrota and Mench, 1994; Nelms and Avery, 1997), based on the fact that some of these colours may be innately aversive, while others have found that dull, inconspicuous or lowly preferred colours are also effective (e.g. Hartley, 1999). No comparative study has been conducted to specifically test which types of colours are most effective, but I suggest that any colour that is novel, contrasts with its surrounds, is unexpected or presented out of context may be an effective CS. This is because these colours would have no prior association with palatable foods (e.g. positive associations would not need to be unlearned; Guilford and Dawkins, 1991) and even if lowly preferred, may be memorable because of the contrast with their surroundings or context in which there

were encountered (Avery, 1997). In nature, distasteful prey tend to be conspicuously coloured, signalling to predators their unpalatability (aposematism; Cott, 1940), but avoidance responses can be triggered just as well by any novel colour (Jetz *et al*, 2001). In the context of deterring birds from feeding on pest control baits, it may be unwise to present birds with conspicuous or attractive coloured baits, as birds may eat baits and be lethally poisoned before they learn an avoidance response. Instead, lowly preferred, but novel colours may equally reduce birds' propensity to feed on baits, as long as they still effectively function as conditioned stimuli. As such, I chose to further investigate the potential of lowly preferred colours as CS in this thesis.

(2)   Olfactory cues

Until recently, it was believed that many bird species had very poor olfactory capabilities; it is now known that some birds have an excellent sense of smell that matches the anatomical and performance diversity seen in mammals (Clark, 1998; Clark *et al*, 1993). Recent reviews have described the functional and adaptive aspects of avian olfactory and gustatory systems (Bang and Wenzel, 1986; Berkhoudt, 1986; Kare and Brand, 1986; Waldvogel, 1989; Wenzel, 1973), with olfaction being implicated primarily as a navigational aid (Walcott, 1996) and a means of locating food (Bang and Wenzel, 1986). In many non-avian species, olfaction also serves social functions (e.g. determination of sexual state, signals for aggression, recognition of others), but these functions have not been fully explored or demonstrated in avian species (Beauchamp, 1997). Unlike many other animals, most birds, except kiwi, do not sniff (Wenzel, 1968), so obvious olfactory sampling behaviours are absent (Clark, 1998). This does not mean, however, that olfactory sampling does not occur through normal respiration.

Research is lacking for many aspects of the function and nature of avian olfaction. As such, there is little evidence (and very few experiments) to suggest that particular odours are inherently or innately attractive or repellent to birds (Engen, 1982). Learning appears to be critical to the formation of many odour preferences in mammals (Beauchamp, 1997) and there is no reason not to expect similar learning to occur in birds. However, this type of learning needs to be experimentally demonstrated. The olfactory system of mammals and birds rapidly adapts to odours

and loses sensitivity with repeated or continuous exposure (Engen, 1982). Thus, birds could rapidly habituate to a repellent odour unless it is paired with another repellent that targets different sensory systems (Beauchamp, 1997). When being considered for deterring birds, olfactory signals may function best when used as conditioned stimuli for other secondary repellents. This is because the effects of the olfactory cue alone may wane, but it may remain effective if paired with a secondary repellent.

Addition of a novel odour cue can enhance food avoidance learning in birds (e.g. Roper and Marples, 1997), but some odours appear to be less effective for enhancing avoidance learning towards secondary repellents than visual cues (Mason and Reidinger, 1983) or tastes (Beauchamp, 1997). However, 'warning odours', such a methyl pyrazines used in insect defence against predators, can enhance and elicit strong avoidance responses when paired with other novel cues in food, such as colour (Guilford *et al*, 1987; Marples and Roper, 1996; Rowe and Guilford, 1996). Roper and Marples (1997) also demonstrated that when presented simultaneously to domestic chicks, the effects of almond flavour were stronger and overrode the effects of a colour cue, indicating that odours have the potential to exert more powerful control over feeding behaviour than visual cues in some circumstances. In mammals such as rats, it appears that for some odour cues, their value as conditioned stimuli depends on the strength of the UCS associated with them (Andrews and Braveman, 1975; Nacham and Ashe, 1973). When the UCS causes a strong UCR, odour cues may be particularly effective CS. Therefore, odour cues may be excellent candidates as CS when paired with highly effective UCS. Further investigation of odour-based cues for use in combination with secondary repellents is warranted.

(3)   *Taste cues*

Compared to olfaction, there appears to be only a limited number of tastes that most animals can sense, the main ones being sweet, sour, salty and bitter (Beauchamp, 1997). Although these taste categories are derived mainly from human studies, these tastes appear to be common to many animals (Beauchamp and Mason, 1991; Clark, 1998). Birds appear to be similar to mammals in their ability to detect different types of tastes, with species-specific sensitivity reflecting the ecology and food habits of different bird

species (Berkhoudt, 1986). In every species that it has been tested, taste appears to function purely in the role of regulating nutrient intake and utilisation (Beauchamp, 1997) and avoidance of poisonous substances (Beauchamp and Mason, 1991). While the exact role of taste has not been determined for many avian species, I believe it is reasonable to assume that taste will also function in the roles of nutrient uptake and poison avoidance for most birds. Tastes have excellent potential for repellency (Beauchamp, 1997) and offer a promising avenue for repellent development.

Innate taste preferences and aversions are often expressed by birds and other animals at first exposure, with little evidence of prior learning required for an animal to respond appropriately (Beauchamp, 1997). For example, many animals avoid bitter compounds when first exposed to them, although the threshold at which different species reject bitter substances varies widely (e.g. Jacobs *et al*, 1978). Birds appear to tolerate higher concentrations of bitter substances (i.e. they will continue eating bitter foods) compared to some mammals (Clark, 1998; Wenzel, 1973). This suggests that birds and mammals do differ somewhat in their taste perception. While bitter substances would be unlikely to be appropriate for the development of effective avian repellents that need to be palatable for mammals, other differences in taste perception between birds and mammals may be an avenue for finding avian repellents.

Aversion learning plays an important role in the ongoing responses of birds and mammals to different tastes (Clark, 1998). A number of studies with birds and mammals have demonstrated that positive or neutral tastes (tastes that have previously been associated with a reward, like high energy content food) can become highly aversive if paired with an appropriate UCS (Garcia *et al*, 1974; Schuler, 1983). Likewise, preference for lowly preferred tastes can be increased by association with positive post-ingestional consequences (e.g. Provenza, 1995).

There are several examples of effective avian repellents that rely, at least in part, on taste to mediate both unlearned and learned avoidance responses (e.g. methyl anthranilate; Mason *et al*, 1989). Repellents based on taste cues may have primary (e.g. methyl anthranilate) or secondary (e.g. methiocarb; Mason and Reidinger, 1983; Nelms and Avery, 1997) modes of action for birds, but naturally all require sampling or ingestion of some of the treated food before repellent effects occur (Clark, 1998). As such, taste-based repellents may pose a greater risk of poisoning to non-target birds than visual or olfactory repellents, because the birds have to sample some pesticide bait

before being repelled. In reality however, most repellents that act via taste cues also target other sensory systems. For example, methyl anthranilate provides strong taste cues, but also acts via olfactory cues (Marples and Roper, 1997) and chemethesis (sensory irritation/pain; Clark, 1998). Mason and Otis (1990) found that taste alone (methyl anthranilate; in the absence of visual, olfactory or chemesthetic cues) was not a sufficiently strong stimulus to prevent feeding by red-winged blackbirds and starlings. Like most repellents, taste-based bird repellents (primary or secondary) have been demonstrated to be more effective when paired with other salient CS, such as colour (Beauchamp, 1997; Mason and Clark, 1996) or odour (Marples and Roper, 1997; Roper and Marples, 1997).

(4)   *Tactile cues*

Compared to the other senses, very few published data exist on the ability of different bird species to detect textures, although there is some evidence that birds are sensitive to tactile cues. Tacky pastes and liquids (usually containing polybutene) repel birds from roosting sites or other structures (Timms, 1983), presumably though tactile sensations on the feet or body. Birds also make discriminations between foods based on textural properties and will use texture as the basis for dietary selection (Best and Gionfriddo, 1994). Seeds that have been treated with particulates of various compositions (e.g. clay, lime, cement, charcoal) will be partially avoided by birds. Blackbirds (Decker and Avery, 1990), starlings (Mason and Clark, 1994), snow geese (*Chen caerulescens*; Mason and Clark, 1995), Canada geese and brown-headed cowbirds (Belant *et al*, 1997a, b) all reduce seed consumption if the seeds are coated with particulates. However, when bird numbers are high and/or alternative foods are scarce or unpalatable, they will begin to consume particulate-treated food before they will begin consuming foods treated with visual- or taste-based repellents (Mason and Clark, 1997). This suggests that compared to other repellent types, particulate repellents have a reasonably weak effect on birds.

Tactile cues have been hypothesised to function in several ways, but none have been proven experimentally. The increased coarseness of particulate-treated food may be abrasive, causing gastro-intestinal irritation (Nir *et al*, 1994). Alternatively, the coarseness may change the perception of the food to birds such that they consume it in

only small quantities as grit (Clark, 1995). Further, the chemosensory cues associated with some particulate substances may render food unpalatable (e.g. lime increases pH; Belant *et al*, 1997a, b). Based on the data available, tactile cues may offer some potential as repellents, but do not appear to be as likely to cause long lasting avoidance as other cues.

(5)   Irritant (Chemesthetic) cues

The trigeminal system is involved in the detection and response to irritating or painful chemical stimuli (chemethesis; Clark, 1998). Sensations are transmitted over the fifth cranial nerve (trigeminal) and are described by humans as sensations of tingling, itching, burning, pain or cooling among other things (Beauchamp, 1997). Relatively little is known about the role of chemesthesis as a primary cue for repellency in birds, but strong sensations elicited by the trigeminal system are almost universally regarded as unpleasant and are immediately avoided by all animals (Beauchamp, 1997). Avoidance of chemesthetic cues could result from direct contact and stimulation of the nerves in the oral cavity, or exposure of nociceptive fibres in the eye or oral-nasal cavity to volatiles (Clark, 1998). The responses exhibited by some humans when exposed to freshly chopped onion or when eating chilli peppers are good examples of the trigeminal system in action.

   Several repellents appear to act via chemesthesis. Anthranilates, which have significant taste and odour properties, are much less effective repellents when the trigeminal system is compromised (Clark, 1996; Mason *et al*, 1989), suggesting chemesthesis is an important component of the avoidance response. Other compounds, such as *o*-amino acetophenone and coniferyl benzoate also elicit chemesthetically-mediated avoidance responses (Clark, 1998). It appears that there is an interaction between chemesthetic, olfactory and gustatory systems when stimuli are presented to birds, with each component contributing to repellency (Mason *et al*, 1989). The exact roles of each of these components have not been determined however. Chemical irritants appear to be excellent candidates as bird repellents as they are innately aversive and often require no ingestion to have a repellent effect (Beauchamp, 1997), However, little is known about whether birds will become more or less sensitised to the irritants over time, with evidence suggesting that desensitisation occurs for some oral irritants (Green, 1991).

Promising options for repelling birds from baits

Any bird repellent must meet several criteria to be suitable for use in pest control baits. Most importantly, the repellents must cause rapid and long-lasting avoidance of the toxic food (for as long as the bait remains toxic and palatable to wild birds), and this is the focus of my research. Ideally a repellent would entirely prevent feeding, but if not, must at least prevent lethal poisoning of birds. Repellents must not compromise the efficacy of pest control: possums and rats must still be lethally poisoned by repellent-treated baits under a wide range of conditions. I did not investigate this issue as part of my thesis, but in related research some data have been collected on the acceptance of baits treated with the specific repellents I used in this study (see sections below describing the individual repellents I studied for comment on acceptance by pests). Additionally, repellents need to be able to withstand the bait manufacture process, be stable and persistent, be readily available and be low cost (Day *et al*, 2002). From the information I have described above on primary and secondary repellents and on repellent cues and sensory systems in avian species, several obvious avenues exist for designing repellents that will be suitable for pest control baits.

Repellents with primary or secondary modes of action, or combinations of repellents using both modes may all have potential for reducing birds' propensity to eat baits. Primary repellents may initially prevent birds from sampling bait but do not usually promote long-lasting avoidance (Domjan, 1998), so birds could be at risk of poisoning if they habituated to the repellent effects. Secondary repellents produce long-lasting avoidance but require birds to ingest treated food before learning can occur (Clark, 1998a), so accidental poisoning could arise if avoidance learning (or deterrence due to primary repellency effect) did not occur before the bird had consumed a lethal quantity of the treated food.

Combinations of repellent stimuli may be more effective at deterring birds from baits than single repellents. Several researchers have found that addition of a visual cue enhances avoidance learning towards repellents (Greig-Smith and Rowney, 1987). By combining secondary repellents with salient olfactory, visual or taste cues, especially if these also served as primary repellents, it may be possible to achieve high and rapid rates of repellency. Further, it may be possible to achieve high

repellency using lower concentrations of potentially toxic substances (Avery and Mason, 1997; Nelms and Avery, 1997; Sayre and Clark, 2001).

Several types of cue appear to have excellent potential as repellents in their own right or as conditioned stimuli for other secondary repellents. Novel visual cues (in particular lowly preferred colours), olfactory cues or irritants appear to have the most potential, and may reduce initial food sampling by birds. The same substances may also provide effective CS for a secondary repellent. Data on the potential for tastes and tactile cues to provide effective repellency are less robust, but either type of cue could also be an effective CS if it was novel, detectable and paired with an appropriate secondary repellent. Therefore, for my thesis research, I selected a range of repellent compounds reported to have varying modes of action. These compounds rely on several different sensory cues to have their effect, so my thesis provided an opportunity to compare the efficacy of compounds that target different senses.

Repellents and cues chosen for this study

Based on the requirements of a bird repellent for use in pest control baits, knowledge of the sensory abilities of birds, and the most promising options for repellency I identified above, I chose to investigate the following repellents and cues:

Neem oil

Neem oil (an extract from the Neem tree, *Azadirachta indica*) is a bitter substance that has recently become available as a botanical insecticide. The active ingredient, azadirachtin, is a triterpenoid that is reported to effectively repel a range of insects from feeding (Gahukar, 1996). Neem oil causes immediate reduction in the food consumption of starlings at a 2% concentration (Mason and Matthew, 1996) suggesting it is a **primary** repellent. Neem cake, another extract containing azadirachtin, has also been demonstrated to deter parrots (*Psitacula krameri*), weaverbirds (*Ploceus phillippinus*) and house sparrows (Rao *et al*, 1990; Shivanarayan and Rao, 1988) from feeding. Only a few grams of food ingestion are required to repel the birds. It is thought that neem acts via aversive taste cues, but the exact mechanism by which repellency occurs has not

been determined (Mason and Matthew, 1996). There is some evidence that the efficacy of neem products containing azadirachtin can vary, as chickens (Salawn *et al*, 1994) and Brahminy mynas (*Sturnus pagodarum*; Patel *et al*, 1992) readily consume neem seeds.

I chose neem oil as a candidate repellent for this thesis because: (1) it has been demonstrated to repel some birds; (2) as a primary repellent (suggested to act via aversive taste cues) it may reduce bait sampling quickly enough to help prevent lethal poisoning of non-target birds that eat bait; (3) target pest species, such as possums and wild rodents (rats and mice) readily accept lethal quantities of carrot baits treated with neem oil (Day *et al*, 2000); (4) it repels invertebrates, which may help to reduce secondary poisoning of insectivorous birds; and (5) it is readily available and low in cost compared to many synthetic repellent compounds (Mason and Matthew, 1996).

Agricultural lime

Agricultural lime is a **primary** repellent that deters birds from treated food at first exposure, apparently due to both its granularity (texture) and its high pH (potential irritant; Clark and Belant, 1998). Birds that have been repelled from food by particulate agricultural lime include Canada geese (Belant *et al*, 1997a) and brown-headed cowbirds (*Molothrus ater*; Belant *et al*, 1997c), although Cummings *et al* (in prep.) found that lime did not repel red-winged blackbirds (*Agelaius phoeniceus*) from feeding. Birds are generally repelled by aqueous solutions of > 12 pH (Feurst and Kare, 1962), and are only deterred by particulate lime if the pH is 11.4 or more and the particle size is at least 150 μm (Clark and Belant, 1998). Lime usually suppresses feed consumption by up to 50%, but does not completely prevent consumption (Clark and Belant, 1998). Avoidance of lime-treated food may be due to its texture or some caustic effect (perhaps causing trigeminal stimulation) on mucous linings of the mouth caused by elevated pH (Belant *et al*, 1997c).

I chose agricultural lime as a candidate repellent because: (1) it has been demonstrated to repel several bird species from feeding; (2) as a primary repellent acting via tactile or irritant cues it has excellent potential to prevent feeding with only minimal contact between the bird and the bait, reducing the risk of immediate poisoning; (3) carrot and paste baits treated with agricultural lime are readily consumed by captive and wild

possums and by captive rats (Day *et al*, 2000); and (4) it is extremely inexpensive and could readily be incorporated into cereal baits or onto the surface of carrot baits.

D-pulegone

D-pulegone (CAS No. 89-82-7) is a volatile compound (a type of peppermint) that acts as a **primary** repellent for birds via odour cues, taste (Wager-Page and Mason, 1996) and irritant properties (Ballinger, 1999). In choice and no-choice feeding tests, it repels captive birds of several species (at a concentrations ranging from 0.1% to 1%), including starlings (Mason, 1990), red-winged blackbirds (Avery *et al*, 1996), brown-headed cowbirds (Belant *et al*, 1997b) and northern bobwhites (*Colinus virginianus*; Mastrota and Mench, 1995b). D-pulegone typically reduces food consumption by at least 50% (e.g. food consumption of starlings was reduced by 53% when offered food treated with 1% d-pulegone; Wager-Page and Mason, 1996). However, direct contact with d-pulegone-treated food produces a stronger avoidance response for starlings than when offered food in association with (but not containing) volatile d-pulegone (Wager-Page and Mason, 1996), so additional cues such as colour or texture may be required to reduce consumption if only volatiles are used (Mason and Epple, 1998). Mason and Primus (1996) evaluated the efficacy of alternative menthone derivatives for preventing starlings from feeding and found that d-pulegone and dl-pulegone were more effective as repellents than any other menthone derivative. In a separate experiment with red-winged blackbirds, pennyroyal oil was found to be nearly as effective at preventing feeding as d-pulegone (Avery *et al*, 1996). D-pulegone is suggested to be a more effective repellent than Optamint, which effectively prevents sparrows from feeding in New Zealand (Porter, 1997).

I chose to investigate d-pulegone as a candidate repellent because: (1) it has been demonstrated as a highly effective feeding repellent for several bird species and more data has been collected demonstrating the efficacy of d-pulegone than for any other menthone derivative; (2) as d-pulegone acts partially via volatile cues and taste, it may repel birds without them having to contact the food (or with only a very small taste), making it ideal for incorporation into poisonous baits; (3) it is readily accepted in lethal quantities by possums and rats when presented on carrot, cereal or paste baits at

concentrations of 2% or less (Day *et al*, 2000); and (4) it is readily available and could easily be paired with additional repellent cues in a bait.

Avex^{TM} *- anthraquinone*

Avex^{TM} (Loveland Industries Inc., USA) is a commercially available anthraquinone-based repellent. The product contains 9,10-anthraquinone (50% wt/wt; CAS No. 84-65-1) as the active ingredient. Anthraquinone has been recognized as an effective avian feeding deterrent since the 1950s (Neff and Meanley, 1957), but to date, no research has been published on the product Avex. The repellent properties of anthraquinone and of Flight Control^{TM} (Environmental Biocontrol International, USA), an anthraquinone-based product similar to Avex, have been evaluated on several bird species over recent years using a range of experimental procedures. In choice and no-choice tests, anthraquinone reduces food consumption of captive red-winged blackbirds and boat-tailed grackles (*Quiscalus major*) by 71% to 84 % at a 0.5% concentration (Avery *et al*, 1997). Flight Control (containing 50% anthraquinone) effectively reduces food consumption (by 64 to 100%) of brown-headed cowbirds, Canada geese and sandhill cranes (*Grus canadensis*) at a 0.5% - 1% concentration (e.g. Avery *et al*, 1998, 2001; Blackwell *et al*, 1999, 2001; Dolbeer *et al*, 1998). When no alternative food sources are available, food consumption of house sparrows is halved by a 0.6% concentration of anthraquinone (Schafer *et al*, 1983). There is some evidence however, that Flight Control does not always reduce feeding by red-winged blackbirds and horned larks (*Eremophila alpestris*) in the field, not because it is not effective, but because the repellent washes off treated vegetation before all birds have been exposed to its negative effects (Avery *et al*, 2000; York *et al*, 2000).

Anthraquinone is reported to be a **secondary** repellent that operates via a conditioned taste aversion. Birds are observed during experiments to taste and eat anthraquinone-treated food, experience negative post-ingestional effects within a few minutes (often including vomiting), and from then on avoid the treated food in all subsequent exposures (Avery *et al*, 1997). Similar illness-induced avoidance has been observed when captive tits (*Parus* spp.) feed on anthraquinone-treated insect larvae (Hilker and Köpf, 1994). Claims that anthraquinone acts via secondary repellency have been based on these illness observations, with the mode of action of the repellent being implied from the

behaviour of birds post-ingestion. However, I have found no published studies that have formally evaluated the mode of action of anthraquinone. This lack of rigorous experimentation is in marked contrast to typical experiments that are conducted to demonstrate the effects of aversion conditioning agents on rodents (e.g. see Gustavson, 1977). Despite this, other evidence from avian experiments with anthraquinone is also suggestive of learned avoidance. Individual red-winged blackbirds, boat-tailed grackles, Canada geese and brown-headed cowbirds offered anthraquinone-treated food all readily eat the food when first exposed to it, with little evidence of primary repellency (Avery *et al*, 1997; 1998; Dolbeer *et al*, 1998). Further, each of these species either eats progressively less (or completely rejects) the treated food over time (suggesting learning). In no studies have birds begun to eat more anthraquinone-treated food over exposures, unless the anthraquinone treatment has washed off the treated food (Dolbeer *et al*, 1998). Anthraquinone is described as having some irritant properties (Windholz, 1983) and a "bad" taste (Schafer, 1991), but no experiments have demonstrated an aversion by birds to the taste of anthraquinone. When offered anthraquinone-treated food, red-winged blackbirds and boat-tailed grackles do not perform any head shaking or bill wiping responses typical of birds exposed to primary taste repellents (Avery *et al*, 1997). This suggests that, for these species at least, there is no aversive taste associated with anthraquinone. Therefore, although Avex may have some taste (and possibly irritant or visual) cues associated with it, I suggest that Avex acts predominately via secondary repellency. I consider it to be a secondary repellent for the purposes of my research, although further classical conditioning studies to test this contention would be useful.

I chose Avex (containing 50% anthraquinone) as a repellent for this research because: (1) anthraquinone is one of the most effective avian repellents currently known; (2) as a secondary repellent, Avex offers the potential for long-lasting avoidance of baits for the duration of their toxicity in the field; (3) anthraquinone does not appear to possess strong primary aversive cues (visual, odour or taste), so could be effectively combined with other sensory cues for enhanced avian repellency; (4) captive and wild possums readily eat lethal quantities of cereal and carrot baits treated with up to 2% concentration of Avex (Day *et al*, 2000), and captive rats are also readily poisoned (T. Day, *unpublished data*); and (5) Avex is already commercially available in New Zealand for other repellent applications, is low cost and can readily be incorporated into or onto pest

control baits. It is not known whether wild rats will be poisoned by baits treated with Avex, and current research is addressing this issue.

Blue colour

As described above, avian colour vision is highly sophisticated and appears to be the primary sense used by many birds in food selection (Avery, 1997; Avery and Nelms, 1990; Gillette *et al*, 1983). There is ample experimental evidence that visual cues enable many bird species to discriminate between palatable and repellent foods (e.g. Avery and Mason, 1997; Mason and Reidinger, 1983; Nelms and Avery, 1997). Further, visual cues (e.g. red colour) have been found to enhance the effects of secondary repellents (e.g. Mason and Reidinger, 1983; Nelms and Avery, 1997). As such, visual cues are an obvious possibility for incorporating into effective avian repellent design.

Research in New Zealand with native birds has demonstrated that birds will select foods based on colour cues and readily show colour preferences. When given a choice between red, yellow, brown, green and blue foods, weka and robin least preferred blue colour (Hartley, 1999; Hartley *et al*, 1999; 2000). However, both species readily habituated to and began eating all of the colours offered within a few days (Hartley, 1999), suggesting that colour alone would be unlikely to be an effective long-term repellent for pest control baits. However, using a lowly preferred colour, such as blue, may reduce initial bait sampling, and if paired with a secondary repellent that caused longer-term bait avoidance, may be an effective strategy for repellent design.

I chose blue colour as a cue for investigation in my research because: (1) it has been demonstrated to effectively reduce food consumption for native New Zealand birds, especially at first exposure; (2) colour has previously been demonstrated to have potential as a cue for enhancing the effects of other repellents; (3) possums readily eat lethal doses of blue coloured bait (Day and Matthews, 1999); and (4) blue colour could be incorporated into any bait type and would add no additional cost to baits, as all possum baits currently used in New Zealand have to be dyed green.

Methods for testing repellents

Most studies on bird repellents have evaluated the efficacy of one or more compounds for deterring birds from feeding, and have not formally tested the mode of action of the repellents. Efficacy studies have typically used wild or captive birds, single birds or flocks and choice or no-choice methods. The pros and cons of these options, and implications for the studies undertaken in my thesis are presented below.

A wide range of experimental methods have been used in the past to evaluate the efficacy of avian repellents, reflecting the varied aims of the studies (and affecting to some degree the quality of data gathered). In general, studies on the efficacy of repellents have used methods that have tested whether a range of concentrations of a given repellent reduce food consumption by birds (e.g. is d-pulegone repellent to red-winged blackbirds? - Avery *et al*, 1996), rather than testing the mode of action of the repellent (Clark, 1997). Only a few researchers have used designs to test learning theory or roles of cues (e.g. colour avoidance learning experiments; Mason and Reidinger, 1983; Mastrota and Mench 1994; 1995a). As such, many descriptions of the mode of action of repellent chemicals are made by implication from the pattern of food consumption observed, rather than by experimental proof of the mechanisms driving repellency. Compared to data on feeding behaviour and learning in mammals (e.g. avoidance learning in rodents; Andrews and Braveman, 1975; Nacham and Ashe, 1973), there are fewer data available on bird repellents.

When interpreting the results of experiments assessing avian repellents, the context in which the experiments were conducted, and the situations in which the repellents are to be used in practice, are both important. Repellents may be tested against individual birds or flocks or populations of birds. For birds that usually feed without conspecifics (e.g. New Zealand robins) studies of the feeding responses of the individual animals are useful (e.g. Hartley, 1999). These studies provide good data on the consumption of repellent-treated foods by individual birds and the variability in reactivity of individuals to a given repellent. For flocking species, however (e.g. house sparrows), it is valid to test birds with repellents in a group situation, rather than individually. The feeding choices of flocking birds are affected by the choices and behaviour of their flock mates (Reidinger and Mason, 1983; Ward and Zahavi, 1973). However, experiments with flocks of birds do not allow determination of the proportion of the population that are more or less likely to consume repellent-treated

food. Additionally, composition of wild bird flocks may vary from exposure to exposure, potentially masking any temporal changes in repellent effects. Population turnover and day-to-day changes in flock composition were suggested to reduce the effectiveness of an anthraquinone-based repellent formulation, Flight Control, for preventing red-winged blackbirds from feeding on wild rice (Avery *et al*, 2000).

Another important consideration in repellency experiments is whether captive or wild birds are used. Experiments involving individually housed or groups of captive birds have been used extensively. Captive bird experiments can be useful, as they allow for easier measurement of the feeding behaviour of birds to a wide range of repellents or concentrations (e.g. Avery *et al*, 1997). However, these experiments can only mimic natural feeding situations, and may be of little relevance in a wild context. Studies with wild birds, if designed well, can closely mimic the feeding situation in which a repellent is required to work. For example, a repellent can be applied to a crop and depredation of the crop by wild birds can be measured over time (e.g. York *et al*, 2000). Therefore, birds are comparing the palatability of the repellent-treated food provided in the experiment, to other food sources naturally available in their habitat. Unfortunately, in many studies with wild birds it is not possible to identify individuals, so it is difficult to determine why different patterns of food consumption or repellency are occurring over time or between experiments. A number of researchers have used both captive and free-ranging birds to evaluate the same repellents. In theses studies, the results of captive experiments have sometimes been replicated and applied in the wild (e.g. Avery *et al*, 1998). However, the repellent effects observed in captivity are not always reflected in the feeding responses of free-ranging birds. For example, Avery et al (2000) found that the repellent Flight Control effectively prevented feeding by red-winged blackbirds in pens, but did not stop depredation of newly planted rice crops by the same species. The repellent was ineffective in the field because the method of application used in pens was unable to be replicated in practice. As such, the choice between using captive or wild experimental subjects should be determined largely by whether captive experiments will effectively mimic the practical situations for which the repellents are required.

The efficacy of repellents can also be evaluated using choice or no-choice test methods. Choice tests provide an excellent opportunity to measure the relative

consumption of different baits by individual birds. These tests have been used widely to compare different repellents at the same time or different concentrations of the same repellent, with the same individuals under controlled conditions (e.g. see studies describing avian anthraquinone repellency in Ballinger, 1999; 2001). Choice tests make excellent use of each bird that is used, as every bird can be exposed to the range of repellents. This removes inter-bird variability, potentially allowing for highly accurate comparisons between substances (Clark, 1997). No-choice tests, in which the birds are presented with a single bait type only, differ from choice tests, in that comparison between repellents must be made between birds or within birds at different time periods. No-choice tests, therefore, always have either inter-bird variability or temporal variability in a within-subjects design. This can make no-choice tests less sensitive for determining the relative repellency of different substances (Clark, 1997). However, no-choice tests may better reflect the way in which birds will encounter foods in a natural foraging situation and many animals, including birds, are considered to be less sensitive to the effects of repellents in no-choice tests than in choice tests (Clark, 1997). Further, if a substance is repellent in a no-choice test it is almost always repellent in a choice test and in the field (Clark, 1997).

In this thesis, I chose a range of choice and no-choice experimental methods with which to evaluate repellency for the different bird species. I used mainly choice tests, because I wanted to directly compare different repellent treatments, and wild birds always have choices when they are feeding naturally. I also used a no-choice test design in one study, to determine the applicability of the choice test data to the situation in which native birds may encounter pest baits. The test methods I chose were also designed to gain the maximum quantity and quality of data on repellent efficacy, from a limited number of individual birds or flocks. The methods used for native birds were designed to mimic the situations in which birds may find baits in the wild. Like many other repellent studies, my methods were designed primarily to determine whether repellents had an effect on feeding behaviour (food consumption), rather than to specifically identify the mechanisms by which any effect occurred. This means that I could only suggest what mechanisms were driving repellency for any repellent, based on the feeding behaviour observed. I chose to study wild birds because they were readily available and, as the overall aim of this thesis was to

identify a repellent that could deter free-ranging native birds from feeding on pest control baits in New Zealand forests, their feeding responses were highly relevant to the outcome of my research.

Bird species chosen for this study

I chose one introduced bird (the house sparrow) and two native New Zealand birds (North Island robin, North Island tomtit) for my research. In this section, I describe the rationale for choosing each species and what is known about the feeding behaviour of each species in relation to repellents or baits.

House sparrow (*Passer domesticus*)

House sparrows (Figure 1) were chosen for this study as a 'model' species for testing the efficacy of repellents. Although my thesis focuses primarily on using repellents to modify the feeding behaviour of native birds towards pest control baits, there are only limited numbers of individuals of any native species available as experimental subjects. As such, I felt it was prudent to begin the research with repellents using a common introduced species. From that research, only repellents with high potential would be evaluated with native species, making best use of the native birds available.

   House sparrows are an ideal model species for several reasons. Free-ranging sparrows are one of the most widely available avian species in New Zealand (Heather and Robertson, 1996). Sparrows are non-migratory and wild birds can readily be trained to use feed tables (e.g. Porter, 1997). Once reliably using a food source, sparrows are extremely difficult to deter from feeding (Porter *et al*, 1994). They are also probably the most economically important bird pest in New Zealand, causing serious damage to wheat, barley and maize crops, and attacking grapes, cherries and other fruits before they fully ripen (Heather and Robertson, 1996; Porter *et al*, 1994). Therefore, while my primary intention was to use house sparrows as a model against which to test the effects of a range of repellents, the results of my sparrow research may have applications for the prevention of crop damage caused by sparrows or other species with similar feeding behaviour.

Figure 1:   *House sparrows feeding on trays of wheat from a table in Hawke's*
                Bay, New Zealand. Inset: Male house sparrow.

The efficacy of several repellents for deterring sparrows from feeding has been
reported previously. Sparrows avoid familiar or novel food sources treated with
chemicals reported as primary repellents, such as quinine sulphate, tannic acid, Optamint
and cinnamamide (Greig-Smith, 1987; Moran, 2001; Porter, 1997). These chemicals act
via aversive olfactory, visual or taste cues. Sparrows also assess foods on the basis of
visual cues, avoiding black or blue food, and preferring to eat red, yellow or white foods
(Gionfriddo and Best, 1996; Greig-Smith and Rowney, 1987; Pawlina and Proulx,
1996) in much the same manner as they avoid other primary repellents. Sparrows also
readily learn to avoid secondary repellents, such as methiocarb (Greig-Smith and
Rowney, 1987; Porter, 1977). It appears that sparrows are much more tolerant of some
repellents than other bird species. For example, sparrows were only repelled from
methyl anthranilate after being exposed at doses eight times higher than the
concentration required to deter feral pigeons (*Columba livia*) (Moran, 2001). This
makes the sparrow model a robust and conservative test of repellent efficacy for other
species.

I was uncertain how the feeding behaviour of sparrows towards repellents would relate to that of the native birds of interest in my research. However, sparrows tend to be one of the most difficult bird species to deter (Porter *et al*, 1994) and repellents that are effective with one species are generally repellents to others. For example, anthraquinone, the active ingredient in Avex (one of the repellents evaluated in my thesis), has been demonstrated to repel at least 19 avian species, with only four species reported to not be repelled by anthraquinone (Ballinger, 1999, 2001). On the occasions anthraquinone did not deter birds, the application method appeared to be at fault, rather than the repellent compound (e.g. Avery *et al*, 2000). Although sparrows are flock feeding species and the native birds I tested were not, I considered that repellents that were effective for sparrows were highly likely to be effective repellents for native birds.

New Zealand robin (*Petroica australis*)

The New Zealand robin (Figure 2) is a small (18cm, 35g) territorial passerine that lives in native and exotic forest. It is a member of the family Eopsaltriidae, of which there are three species endemic to New Zealand, the New Zealand robin, the tomtit and the black robin (*Petroica traversi*). There are three geographically isolated sub-species: North Island robin (*P. a. longipes*), South Island robin (*P. a. australis*), and Stewart Island robin (*P. a. rakiura*). Robins are insectivorous, but supplement their diet with fruits in summer, autumn (Heather and Robertson, 1996) and winter (Hartley, 1999). They feed predominantly on the forest floor by gleaning invertebrates from the leaf litter and rely largely on sight to find their prey (Powlesland, 1981). Robins will sometimes tremble a foot to induce invertebrates to move in response to the vibrations (Heather and Robertson, 1996). Robins are similar in their feeding behaviour to several other small forest birds (e.g. tomtit, fantail, grey warbler, rifleman), but tend to spend more time feeding on the ground (Powlesland, 1981) and be more "confiding" in their nature (Heather and Robertson, 1996).

Figure 2:   *Female North Island robin investigates dough baits on a cleared litter arena on the forest floor.*

I chose to study North Island robins as they are particularly vulnerable to poisoning (Powlesland *et al*, 1999) and have previously been observed eating cereal and carrot baits during pest control operations (Spurr and Powlesland, 1997). It is assumed most robins die from primary poisoning (Spurr, 2000). The most significant impacts on robins have been observed during carrot operations where there have accidentally been small bait fragments (chaff) distributed (Powlesland *et al*, 1999), although similar levels of mortality have been observed during cereal–based control using Talon 20P (e.g. Brown, 1997). Also, wild robins are easily observed and have successfully been used to measure bait colour preferences (e.g. Hartley *et al*, 1999). Robins respond positively towards humans and will approach to take food (Maloney and McLean, 1995), making them an ideal species for evaluating repellent effects in the context of pest control in New Zealand.

New Zealand tomtit (*Petroica macrocephala*)
Tomtits (Figure 3) are smaller than robins (13 cm, 11g), but are similar in many aspects of their breeding biology, habitat preferences and diet (Heather and Robertson, 1996). There are five geographically isolated sub-species of tomtit: North Island tomtit (*P. m.*

toitoi), South Island tomtit (*P. m. macrocephala*), Chatham Island tomtit (*P. m. chathamensis*), Snares Island tomtit (*P. m. dannefaerdi*), and Auckland Island tomtit (*P. m. marrineri*). Tomtits live within native and exotic forests, but tolerate more open forest or scrub than robins and forage from ground level to the top of the canopy (Heather and Robertson, 1996). Like robins, they feed mainly on invertebrates, supplemented by small fruits in summer and autumn (Heather and Robertson, 1996). Tomtits use a 'watch and wait' feeding strategy, usually perching above the ground and scanning a branch or the ground for invertebrate movement, then flying down to capture their prey (Gibb, 1961). Tomtits do not usually turn over or search through leaf litter like robins or blackbirds do (Gibb, 1961), and spend only short periods of time on the ground. When tomtits and robins live in overlapping habitat, robins dominate tomtits, chasing them away from preferred food sources (T. Day, *unpubl. data*).

I chose to use tomtits as an experimental subject in this thesis for several reasons. A significant number of tomtits appear to die during pest control operations (Powlesland *et al*, 2000; Westbrooke *et al*, in prep.), but it is unknown whether they are poisoned via primary or secondary poisoning (Powlesland *et al*, 2000). Unlike robins, tomtits have never previously been observed feeding directly on bait, so the potential of this pathway for poisoning needs to be clarified. Although tomtits and robins are closely related and have similar foraging behaviour (see descriptions above), there may be differences in their susceptibility to poisoning (Powlesland, *et al*, 1999; 2000). During control operations, tomtit mortality appears to be highest during carrot operations, and low or nil during cereal operations (Powlesland *et al*, 2000; Westbrooke *et al*, in prep.). However, carrot-based control operations are generally sown at higher application rates that cereal operations, so it is yet to be determined whether tomtits would be killed during a low sowing rate carrot operation (Westbrooke *et al*, in prep.). In contrast, robin mortality has occurred during carrot and cereal operations, especially where small bait fragments have been distributed (Brown, 1997; Powlesland, *et al*, 1999). This suggests that there may be subtle differences in the feeding behaviour of tomtits and robins. These differences could alter the ability of repellents to protect them from poisoning, so I decided to compare the efficacy of repellent-treated baits for both species.
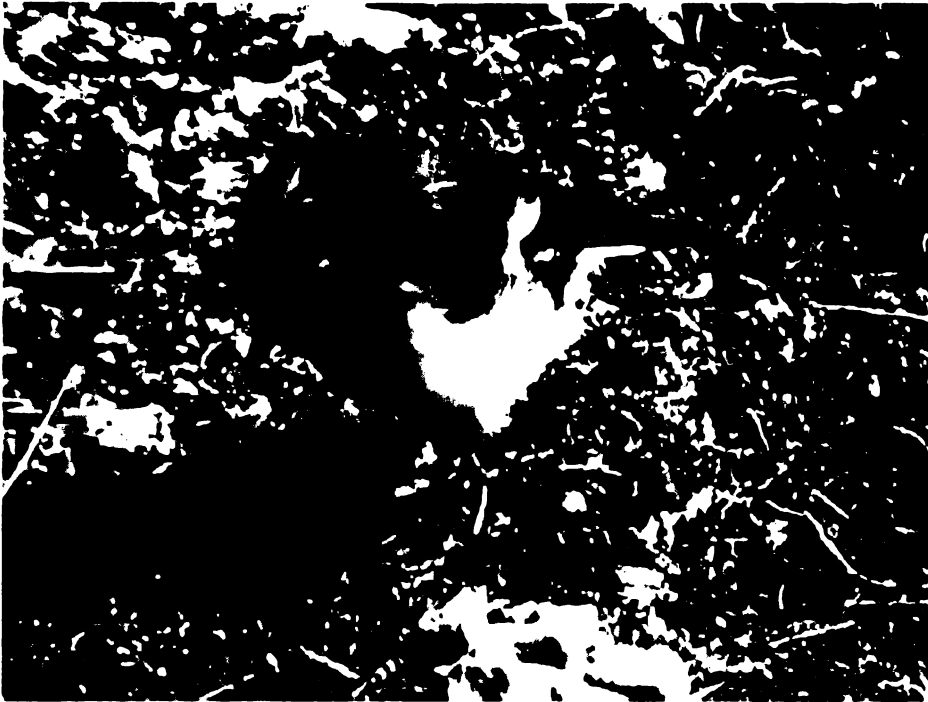
Figure 3:   *Male North Island tomtit searches for invertebrate prey on an area of cleared litter on the forest floor.*

Aim

The aim of this thesis was to investigate the efficacy of repellents for deterring avian species from feeding, with particular emphasis on deterring native New Zealand birds from feeding on pest control baits.

This aim was achieved by conducting a series of experiments evaluating a range of repellents with sparrows, robins and tomtits. The structure and logic for these experiments is described below:

Chapter 2: Responses of free-ranging house sparrows to feed containing primary and secondary repellents.

This chapter consisted of two experiments. In Experiment 1, I determined the efficacy of several concentrations of 4 repellents for deterring sparrows from feeding. The repellents and concentrations I chose were decided on the basis of my review of the

literature on avian repellents and sensory systems. Each chosen repellent had different modes of action and targeted different combinations of sensory cues. In Experiment 2, I investigated the efficacy of combining two of the repellents with different modes of action for repelling sparrows. I chose to do this as literature on repellents and learning suggested that combinations of cues may be more effective as repellents than repellents relying on single cues.

Chapter 3: Repellents to deter New Zealand's North Island robin *Petroica australis longipes* from pest control baits.

In this chapter I also conducted two experiments. In Experiment 1, I refined a methodology for testing repellents, by evaluating robins' preference for three 'standard' green-cinnamon flavoured bait base materials, similar to those used for pest control in New Zealand. I then used the most preferred bait base material in Experiment 2, to compare in choice tests the feeding behaviour of robins towards standard baits and baits treated with the combination of repellents used in Chapter 2. This chapter aimed to determine whether repellents that were effective for deterring sparrows from feeding have any utility in deterring robins from feeding on baits.

Chapter 4: Designer repellents: combining olfactory, visual or taste cues with a secondary repellent to deter free-ranging house sparrows from feeding.

This chapter also consisted of two experiments. The chapter explored whether alternative combinations of repellent cues (to those used successfully in Chapters 2 and 3) could be used to effectively deter sparrows from feeding. The combinations were chosen to test the efficacy of repellents that target different pairings of sensory systems than were targeted in Chapter 2 and to establish which cues appear to be necessary for effective repellency. In experiment 1, I offered sparrows combinations of primary (visual, olfactory or taste cues) and secondary repellents and compared their efficacy. In experiment 2, I compared the efficacy of a combined repellent (visual cue + secondary repellent) with that of a visual cue alone for deterring sparrows from feeding.

Chapter 5: Feeding behaviour of New Zealand's North Island robin *Petroica australis longipes* is modified by combining a novel colour with a secondary repellent.

In this chapter, I determined the efficacy of the visual cue + secondary repellent combination used in Chapter 4 for deterring robins from feeding on baits. I tested the repellent-treated baits in choice and no-choice tests, in different seasons, and using different age classes of birds. These comparisons were made to determine the range of conditions under which the repellent was effective and to identify any individuals in a robin population that may be more vulnerable to poisoning than others.

Chapter 6: Feeding responses of North Island robins and North Island tomtits to pest control baits treated with bird repellents.

In the final experimental chapter, I compared the feeding behaviour of robins and tomtits towards the same baits used in Chapter 5. This experiment was conducted to determine whether subtle differences in the feeding behaviour of tomtits and robins affect repellent efficacy. I also developed a new method for presenting baits to the birds (which was more suitable for testing tomtits) and compared the new method to that used in Chapters 3 and 5.

Chapter 7: General discussion.

This chapter synthesised the findings of my experiments. I also made suggestions for the ongoing development of successful avian repellents.

Summary of thesis structure and content

My thesis presents work I conducted under the supervision of Dr Joseph Waas and Dr Lindsay Matthews. The experimental chapters (Chapters 2 to 6) have been written as scientific manuscripts for submission to peer reviewed journals. Each chapter is presented in the thesis as a complete manuscript, including joint authorship, abstract and relevant references for that chapter. Use of the term 'we' rather than 'I' throughout the research chapters (Chapters 2 to 6) reflects the contribution of the other authors to those chapters. As the manuscripts 'stand-alone' for publishing purposes, there may be repetition of content (e.g. introductory material) between

experimental chapters. The manuscripts have all been submitted to peer-reviewed journals and the style of each manuscript reflects the journal it was submitted to. For ease of reading however, the general formatting and layout of each chapter has been standardised. Chapter 3 has been published and the other chapters are currently undergoing the peer review process. For each chapter, I had overall responsibility for all aspects of the experiments, including selecting the repellents and direction of the research, planning, fieldwork, data collection and writing. My supervisors and other co-authors on each chapter provided valuable advice on conceptual development, trial design, input to the research direction, assistance with fieldwork and editorial suggestions on the content of each chapter. David Duganzich provided valuable statistical advice on all chapters. While I conducted all of the initial analyses, the statistician conducted (with my assistance) the final Genstat analyses reported for most aspects of each chapter.

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Chapter 2

Responses of free-ranging house sparrows to feed containing primary and secondary repellents

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Abstract

The responses of free-ranging house sparrows (*Passer domesticus*) to feed treated
with primary repellents (neem oil, agricultural lime or d-pulegone) and a secondary
repellent (Avex; an anthraquinone-based product) were recorded. Eight independent
populations of house sparrows in Hawke's Bay, New Zealand, were trained to eat
plain hulled wheat from four identical food trays on feed tables. In Experiment 1,
four of the sparrow populations were presented in choice tests with plain wheat and
wheat coated with low, medium or high concentrations of repellent. The
consumption of plain wheat was compared to the consumption of each dose of each
repellent at 1, 2, 3, 8 and 24hr post-offer on four consecutive days. Agricultural lime
reduced wheat consumption in the short-term. However, wheat treated with either
lime or neem oil was consumed by sparrows at the same rate over 24hr as plain
wheat at all doses and on all four test days; this suggests that neither compound was
an effective sparrow repellent. D-pulegone significantly reduced wheat consumption
on Day 1, with birds continuing to eat less of all concentrations of d-pulegone-
treated wheat throughout the four days. Avex did not significantly reduce wheat
consumption on Day 1 of exposure, but sparrows ate progressively less repellent
wheat over each of the following days. For both d-pulegone and Avex, there was a
negative relationship between wheat consumption and repellent concentration. In
Experiment 2, we combined the highest concentrations of d-pulegone (the most
effective primary repellent) and Avex (the secondary repellent) and compared the

efficacy of the combination to the efficacy of Avex alone-treated wheat and plain wheat in choice tests, using all 8 sparrow populations. The combination of 2% d-pulegone + 2% Avex reduced daily wheat consumption significantly more than Avex alone and the effect lasted throughout the 10-day test period. These results clearly demonstrated the potential of the combined repellent for modifying the feeding behaviour of sparrows, and provided evidence for the enhanced efficacy gained by combining primary and secondary repellents.

Keywords: agricultural lime; anthraquinone; Avex; bird repellent; d-pulegone; feeding behaviour; house sparrow; neem oil; *Passer domesticus.*

Introduction

Repellents offer a cost-effective and non-lethal approach for managing conflicts between birds and the commercial and recreational activities of humans (Clark, 1998a, b). Repellent substances are generally classified as primary or secondary (Rogers, 1978). Primary repellents invoke instantaneous rejection responses through sight, taste, smell and/or tactile irritation, and do not require learning to be effective (Clark, 1998a). They are often more benign, and are less effective at promoting long-lasting avoidance responses, than secondary repellents (Domjan, 1998). Secondary repellency results from an illness-induced learned avoidance of the treated food. The degree of avoidance of that food then depends on the strength of the unpleasant experience (Sayre and Clark, 2001). Potent secondary repellents often have undesirable physiological and metabolic consequences, and it may not be desirable to expose wildlife to such effects (Thompson, 1988).

Combinations of repellent stimuli can be more effective at deterring birds than single repellents. Several researchers have found that methiocarb (a secondary repellent) is more effective when paired with either another chemical or a visual cue (e.g. Mason and Reidinger, 1983). It may be possible to combine primary cues or repellents with secondary repellents to either enhance repellency or achieve high repellency using lower concentrations of each substance (Avery and Mason, 1997; Avery and Nelms, 1990; Nelms and Avery, 1997; Sayre and Clark, 2001).

In the present study, we sought to determine the efficacy of three reported primary repellents (neem oil, agricultural lime, d-pulegone) and one secondary bird repellent (Avex), alone and in combination, for deterring the house sparrow (*Passer domesticus*) from feeding. Free-ranging house sparrows were chosen for this study as they were widely available in New Zealand, are non-migratory, and wild birds can be readily trained to use feed tables (Porter, 1997). They are also one of the most economically important bird pests in New Zealand, causing serious damage to a range of field crops such as wheat, barley, oats, maize and peas, and attacking grapes, cherries, strawberries and other fruits before they fully ripen (Heather and Robertson, 1996; Porter, 1977; Porter *et al*, 1994).

The effects of several repellents on the feeding behaviour of house sparrows have been investigated previously. Sparrows avoid familiar or novel food sources treated with primary repellents, such as quinine sulphate, tannic acid, Optamint and cinnamamide (Greig-Smith, 1987; Moran, 2001; Porter, 1997), or secondary repellents, such as methiocarb (Greig-Smith and Rowney, 1987; Porter, 1977). The efficacy of the combinations of repellents investigated in this study have not previously been tested or compared under controlled conditions for their ability to deter house sparrows from feeding, and most repellency studies with sparrows have used captive rather than free-ranging birds. The relative scarcity of seed-eating species in urban and rural New Zealand habitats compared to the variety of species found in Europe and the USA (Heather and Robertson, 1996) means that feed tables open to free-ranging birds will attract virtually only sparrows, eliminating complications associated with inter-species competition. The repellents we chose to evaluate were selected for their proven deterrent effects with one or more bird species, their availability and relatively low cost.

Neem oil (an extract from the Neem tree, *Azadirachta indica*) is a bitter substance that is reported to effectively repel insects from feeding (Gahukar, 1996), and repels starlings (*Sturnus vulgaris*) from feeding at a 2% concentration (Mason and Matthew, 1996). Neem cake, another extract from the Neem tree, has also been demonstrated to be repellent to parrots (*Psitacula krameri*), weaverbirds (*Ploceus phillippinus*) and house sparrows (Rao *et al*, 1990; Shivanarayan and Rao, 1988). Only a few grams of food ingestion are required to repel the birds.

Agricultural lime is a primary repellent that appears to deter birds because of its granularity and its high pH (Clark and Belant, 1998). Birds that are repelled at 12 pH and above (typically 1% to 4 % concentration) include Canada geese (*Branta canadesis*) and brown-headed cowbirds (*Molothrus ater*) (Belant *et al*, 1997).

D-pulegone (CAS No. 89-82-7) is a volatile compound (a type of peppermint) and acts as a primary repellent for birds via both odour cues and by taste (Wager-Page and Mason, 1996). It repels several bird species at a 1% concentration, including starlings (Mason, 1990) and northern bobwhites (*Colinus virginianus*) (Mastrota and Mench, 1995).

Avex (Loveland Industries Inc., USA) is a commercially available anthraquinone-based secondary repellent. The product contains 9,10-anthraquinone (50% wt/wt; CAS No. 84-65-1) as the active ingredient. Anthraquinone has been a recognized avian feeding deterrent since the 1950s (Neff and Meanley, 1957). The repellent properties of anthraquinone and of Flight Control (Environmental Biocontrol International, USA), an anthraquinone-based product similar to Avex, have been evaluated on several bird species over recent years. Flight Control effectively deters brown-headed cowbirds and Canada geese at a 1% concentration (e.g. Avery *et al*, 1998, 2001; Blackwell *et al*, 1999; Dolbeer *et al*, 1998). Anthraquinone operates via a conditioned taste aversion. Birds taste anthraquinone-treated food, experience the negative post-ingestional effects, and thereby learn to avoid the treated food (Avery *et al*, 1997). When no alternative food sources are available, house sparrows are deterred from feeding by a 0.6% concentration of anthraquinone (Schafer *et al*, 1983).

The current study had two specific aims. Firstly, we wanted to identify concentrations of each repellent that would effectively deter free-ranging sparrows from feeding (Experiment 1). The concentrations we tested reflect the range of concentrations of each repellent that have previously been shown to repel bird species. Secondly, we combined the most effective concentration of a primary repellent with Avex to determine whether a combination of primary and secondary repellents was more efficient than either repellent alone as a feeding deterrent for house sparrows (Experiment 2).

Methods

The following experimental protocols were approved by two independent Animal Ethics Committees (Ruakura AEC approval 3136, Waikato University ethics approved).

Study populations

Sparrow populations at eight sites in and around Havelock North, Hawke's Bay, New Zealand were used in these experiments during the early breeding season in the austral spring (August to November 1999). The populations were located in urban or semi-rural privately owned properties and each population had nesting and roosting sites within 100 m of the feed table. The populations were 1.5-5 km apart. As sparrows are routinely sedentary during the breeding season (Heather and Robertson 1996), we considered each population to be independent of the others. We did not identify any individual sparrows in the populations, but based on counts of sparrows within single video frames, there were more than 20 sparrows at all sites. The only other bird species that might feed from the tables were the blackbird (*Turdus merula*) and the greenfinch (*Carduelis chloris chloris*). In 32 h of video footage, only 6 feeding bouts by blackbirds (each of less than 1min duration) were observed, and none by greenfinch, suggesting these species did not play a significant role in the overall wheat consumption patterns at tables.

Experiment 1

In this experiment, we measured the feeding behaviour of four house sparrow populations to wheat treated with three concentrations of neem oil, agricultural lime, d-pulegone or Avex. The concentrations of each repellent chosen for this study represented the range of concentrations that have previously been demonstrated to have some repellent effect on other bird species.

Preparation of repellent-treated wheat   For each of the repellents, we formulated low, medium and high concentration solutions: (1) neem oil (containing 1500 ppm azadirachtin; Plasma Power Ltd, India) at 1%, 2% and 3% concentration diluted in warm water (~35 $^{\circ}$C); (2) agricultural lime (CaCO$_3$; McDonalds Lime

Ltd, New Zealand) at 0.5%, 1.0% and 2.0% concentration diluted in warm water; (3) d-pulegone (CAS No. 89-82-7; Aldrich Chemical Company Inc., USA) at 0.5%, 1.0% and 2.0% concentration diluted in warm water; and (4) Avex (containing 50% 9,10-anthraquinone, CAS No. 84-65-1; Loveland Industries Inc., USA) at 0.75%, 1.5% and 2.0% concentration diluted in warm water. Each repellent solution was applied to the wheat at a rate of 10% of the total wheat weight. The repellent solutions were poured into new plastic containers containing plain wheat and were vigorously mixed through the wheat by shaking the containers for one minute. The wheat was then laid in flat plastic trays to dry (the temperature range in the drying room was 18 to 28 ^{O} C), away from direct sunlight. After being air-dried (for up to 3hr), the treatments were sealed in airtight containers until used. The wheat treatments were prepared between 48 and 72hr before first being offered to the sparrows. Plain wheat was also soaked in water and re-dried in the same manner as the repellent wheat treatments.

Test procedure   A single four-choice feed table was set up at each site (see Chapter 1, Figure 1 for a picture of a feed table). Each table was composed of a 1-m^2 metal platform raised on four legs 1.2m above the ground, on which four food trays were placed. These 25-cm round plastic food trays were arranged in a square pattern, 20-30cm apart (each positioned with respect to a corner of the table). Each table had a roof that extended over the entire table, 50cm above the food trays to protect the food from rain. Sparrows were initially trained to eat plain hulled wheat from all the trays. The training procedure involved placing 50g of fresh wheat in each of the four food trays each day and leaving it there until sparrows discovered it and began eating. Any wheat that had not been eaten each day was removed and replaced with fresh wheat. At all sites, the 200g of wheat offered daily was fully eaten every day after approximately three weeks of training. Once trained, sparrows consumed all wheat they were offered every day. All tables had been supplied with wheat for more than 3 weeks prior to starting the experiments.

During the treatment period, each table was used to present a daily choice between 50g plain wheat and the three concentrations of one repellent (50g each of the low, medium and high concentration in separate food trays). The plain and repellent treatments were allocated to and moved around positions on the table each day using

a Latin square residual effects design. The plain wheat and three concentrations of the repellent wheat were offered to each sparrow population for periods of four consecutive days, with a three-day break between each period, until all four populations had been sequentially exposed to each of the four repellent types.

The pre-weighed quantities of treated and plain wheat were placed on tables between 0700 h and 0900 h each day. The mass of wheat remaining in each tray (to the nearest 1g) was then measured at 1, 2, 3, and 8hr post-offering and all wheat was returned to the trays for the sparrows to continue feeding. We did not measure the mass of each wheat treatment spilled by sparrows in this experiment, because it would not have been possible to distinguish which wheat treatment the spillage had come from, as the treatments did not differ visually. Visual inspections of the tables, and video recordings of sparrows feeding on the tables, indicated that wheat spillage would have accounted for only a fraction of total wheat removed (less than 5g wheat from 200g offered). During each wheat weighing event sparrows flew off the feed table, but always returned and began eating again less than 2 min after the observer moved away from the table. At the end of each 24-hr period all wheat was removed from each tray and weighed. A fresh 50g of each wheat treatment was then placed in the food trays for the next 24hr.

Experiment 2

In this experiment we used all eight sparrow populations to determine the efficacy of combining Avex and d-pulegone for repelling sparrows from wheat. The experiment was conducted over 24 days, eight weeks after Experiment 1 concluded.

Preparation of repellent-treated wheat   The wheat was treated and stored in the same manner as for Experiment 1. There were two treatments: (1) 2% Avex alone (this treatment was identical to the 2% Avex treatment used in Experiment 1); and (2) 2% Avex + 2% d-pulegone – applied as described for Experiment 1 using a solution containing 2% Avex and 2% d-pulegone diluted in warm water. These treatments were prepared in three batches at separate times, as we did not know if the treated wheat would remain repellent for longer than four days. Each batch was prepared between 48 and 72hr prior to presentation. The first batch was fed to

sparrows for the first four days, the second batch for Days 5 to 8, and the third batch for Days 9 and 10 of presentation.

Test procedure   Four-choice feed tables (as used in Experiment 1) were set up and sparrows were provided plain hulled wheat from each of the four 25-cm round tray prior to the treatment period. At all tables the 200g of wheat being offered daily was being fully consumed for more than 3 weeks prior to the experiments.

During the treatment period, sparrows were offered a daily choice between two diagonally-opposed trays of 50g of plain wheat and two trays of 50g of one type of repellent-treated wheat (total = 100g plain wheat and 100g repellent-treated wheat). The experiment was designed as a changeover trial on the eight sparrow populations, with each population offered one type of repellent and plain wheat for a 10-day period, followed by a four-day break and then a second 10-day period in which the populations were offered the other repellent type and plain wheat. Repellents were allocated to the populations and periods in a Latin square arrangement. The position of each wheat treatment was moved to the opposite diagonal on the tables each day so that birds did not associate one position on the feed table with a given type of wheat. We used the same daily routines as in Experiment 1, except that the wheat was measured after only 3hr and 24hr.

Data analysis

All statistical analyses for Experiments 1 and 2 were conducted using procedures in the Genstat 6.1 statistical package (Lawes Agricultural Trust, Rothamsted Experimental Station, Hertfordshire, United Kingdom). Percentage intakes recorded at each time interval (1, 2, 3, 8 or 24hr in Experiment 1, and 3 or 24hr in Experiment 2) were analyzed independently of the others. In both experiments, statistical models included sparrow population, period and population by period as block effects, with a fixed treatment term for repellent. Additional fixed terms used in Experiment 1 were concentration level and the repellent by concentration level interaction. As actual concentrations varied among repellents in Experiment 1 (because the concentrations used for each repellent were chosen to match the range of effective bird repellent concentrations used in previous research), main effect terms were included mainly for analytical convenience. For Experiment 2, an additional term

was used to describe whether sparrow populations had previously been exposed to repellents (in Experiment 1, or in the first part of Experiment 2) or were naïve. In each experiment, the daily data within a four-day or 10-day period were treated as repeated measures data and investigated in two steps: (1) an overall split-plot in time analysis was used to indicate possible time trends within periods; and (2) relevant orthogonal polynomial contrasts among the four or 10 day periods, plus four-day or 10-day averages, and each of the separate days with periods, were analyzed using the population-period changeover design.

In both experiments, intake of plain wheat reached 100% for nearly all populations every day within 3hr, resulting in severe heteroskedasticity, so the plain wheat data were excluded from all statistical analyses. As a result, comparisons involving different repellents involve testing against population-period variation. In addition, in Experiment 1, neem oil and agricultural lime repellents reached 100% consumption at all concentrations for all populations on some days by the 8 or 24hr measurements. On these occasions, the 100% consumption data were omitted from the corresponding analyses. When both neem and lime data were omitted, the changeover design provided no valid test for between repellent comparisons.

Separate day analyses were also carried out (within four-day periods for Experiment 1) with repellent concentrations as separate three-level factors, one for each repellent to provide individual repellent concentration tests. Where neem oil and lime treatments were both excluded from the dataset (due to 100% consumption), analyses were carried out using regression with population and period as fixed effect terms. All other analyses used analysis of variance with population, period, and population by period as random block terms. Data are presented in text as means ± standard error.

Results

Experiment 1

Sparrows consistently removed all the plain wheat that was offered to them throughout the experiment, consuming 90.6 ± 5.2% of it within 1hr and all by 3hr every day. Wheat treated with neem oil did not effectively prevent sparrows from

feeding. Of wheat treated with neem oil, 88.1 ± 2.1% was consumed within 3hr of presentation on all days it was offered, and it was fully consumed within 8hr (Table 1). There were no significant concentration effects at 1-, 2- or 3hr post-presentation, with all concentrations of neem oil-treated wheat being eaten rapidly ($P > 0.5$). Over the 4 days of presentation, neem oil-treated wheat was eaten progressively more rapidly each day (i.e. more wheat had been consumed at one, two and 3hr each day; Table 1, $P < 0.05$).

Table 1:   *Mean percentage consumption of three concentrations of neem oil-treated wheat by sparrows at 1, 2, 3, 8, and 24hr over four days in Experiment 1. L = 1%, M = 2%, H = 3% concentration. Standard errors of the difference (SED) in consumption between concentration means for each time period and day are given.*

Day	Conc.	Time period (hr)				
		1	2	3	8	24
	L	59.3	79.7	85.6	100.0	100.0
1	M	59.7	79.5	84.0	100.0	100.0
	H	53.0	76.3	87.7	100.0	100.0
	SED	8.4	7.0	6.1	-	-
	L	68.2	82.1	88.1	100.0	100.0
2	M	61.9	84.1	87.1	100.0	100.0
	H	53.4	80.6	82.6	100.0	100.0
	SED	7.0	3.7	5.2	-	-
	L	65.8	84.6	92.1	100.0	100.0
3	M	71.4	84.7	91.1	100.0	100.0
	H	66.2	83.5	90.0	100.0	100.0
	SED	6.8	5.0	5.7	-	-
	L	71.0	79.3	86.4	100.0	100.0
4	M	78.3	89.6	92.6	100.0	100.0
	H	77.2	86.2	90.1	100.0	100.0
	SED	9.5	7.4	9.3	-	-

Wheat treated with agricultural lime was also readily eaten by sparrows, with an average of $85.0 \pm 4.2\%$ of wheat eaten within 3hr of presentation and $95.5 \pm 2.5\%$ of wheat eaten within 8hr over the four days (Table 2). On Days 2, 3 and 4 of presentation all treated wheat was eaten over 24hr, except for the High concentration on Day 2. Higher concentrations of agricultural lime significantly reduced the mass of wheat consumed at 1hr post feeding on all four test days ($P = 0.004$), and 2hr post feeding on Day 1 ($P < 0.001$). No other concentration effects were observed. Sparrows ate wheat treated with agricultural lime progressively more rapidly over the four days of feeding (Table 2; $P < 0.05$).

Table 2:   *Mean percentage consumption of three concentrations of agricultural lime-treated wheat by sparrows at 1, 2, 3, 8, and 24hr over four days in Experiment 1. L = 0.5%, M = 1%, H = 2% concentration. Standard errors of the difference (SED) in consumption between concentration means for each time period and day are given.*

Day	Conc.	Time period (hr)				
		1	2	3	8	24
	L	49.0	78.8	83.2	94.1	99.2
1	M	47.3	77.0	78.5	87.0	93.2
	H	13.7	40.4	69.1	82.8	87.9
	SED	8.4	7.0	6.1	7.2	6.3
	L	76.2	81.7	86.1	99.5	100.0
2	M	63.8	81.1	83.1	98.0	100.0
	H	41.7	77.8	79.7	84.7	93.0
	SED	7.0	3.7	5.2	7.2	4.9
	L	77.8	84.7	91.6	100.0	100.0
3	M	72.7	81.6	85.6	100.0	100.0
	H	41.4	78.1	82.1	100.0	100.0
	SED	6.8	5.0	5.7	-	-
	L	76.8	87.2	100.0	100.0	100.0
4	M	71.3	88.6	95.0	100.0	100.0
	H	43.4	80.5	86.5	100.0	100.0
	SED	9.5	7.4	9.3	-	-

Sparrows were deterred from feeding by d-pulegone (Table 3). D-pulegone-treated wheat consumption was numerically lowest on Day 1 of presentation, but no statistically significant time trend was evident (Figure 1A; $P > 0.10$). The highest concentration of d-pulegone (2%) reduced wheat consumption the most ($P = 0.011$), to an average consumption of $66.0 \pm 4.0\%$ (compared to $83.3 \pm 1.9\%$ for 0.5%-d-pulegone and $80.3 \pm 2.9\%$ for 1.0%-d-pulegone). The rate at which d-pulegone-treated wheat was consumed within each day (at 1-, 2-, 3-, and 8hr post presentation) did not change over the four days of presentation (Table 3; $P > 0.1$).

Table 3: *Mean percentage consumption of three concentrations of d-pulegone-treated wheat by sparrows at 1, 2, 3, 8, and 24hr over four days in Experiment 1. L = 0.5%, M = 1%, H = 2% concentration. Standard errors of the difference (SED) in consumption between concentration means for each time period and day are given.*

Day	Conc.	Time period (hr)				
		1	2	3	8	24
	L	31.9	36.4	46.3	66.7	73.1
1	M	27.3	39.6	50.1	70.3	74.6
	H	22.8	37.6	42.5	48.0	52.4
	SED	8.4	7.0	6.1	7.2	6.3
	L	31.6	45.5	59.4	85.6	86.5
2	M	26.0	36.9	43.3	75.1	78.7
	H	18.2	30.7	41.6	66.8	71.5
	SED	7.0	3.7	5.2	7.2	4.9
	L	25.3	37.2	54.9	83.1	86.0
3	M	30.1	38.0	50.9	84.6	89.7
	H	22.8	31.7	45.1	62.4	68.5
	SED	6.8	5.0	5.7	7.6	6.5
	L	37.1	48.9	54.9	84.2	87.5
4	M	27.2	36.1	46.4	70.7	78.1
	H	17.7	31.0	42.4	65.3	71.6
	SED	9.5	7.4	9.3	5.1	3.5

Figure 1: A. *Mean (± SED) daily percentage of each wheat treatment eaten over the four-day test periods in Experiment 1 by sparrows offered a choice between plain wheat and low, medium and high concentrations of d-pulegone. L = 0.5%, M = 1%, H = 2% concentration.* B. *Mean (± SED) daily percentage of each wheat treatment eaten over the four-day test periods in Experiment 1 by sparrows offered a choice between plain wheat and low, medium and high concentrations of Avex. L= 0.75%, M = 1.5%, H = 2% concentration.*

Avex-treated wheat also reduced wheat consumption (Table 4). Sparrows ate 89.9
± 3.2% of all Avex-treated wheat on Day 1 of presentation (not significantly
different from plain wheat consumption; $P = 0.630$), but wheat consumption for all
concentrations decreased significantly over the four-day feeding period (Figure 1B;
$P < 0.05$). There was a significant concentration effect on Day 4 of presentation
only, with the highest concentration (2% Avex) being eaten least readily and the
lowest concentration (0.75% Avex) being eaten most (Figure 1B; $P = 0.002$). The
rate of consumption of Avex-treated wheat decreased over days, with less wheat
being consumed at the 1hr ($P < 0.05$), 2hr ($P < 0.05$) and 3hr periods ($P < 0.05$) each
day compared to consumption on Day 1 (Table 4).

Table 4:   *Mean percentage consumption of three concentrations of Avex-treated
            wheat by sparrows at 1, 2, 3, 8, and 24hr over four days in Experiment 1.
            L= 0.75%, M = 1.5%, H = 2% concentration. Standard errors of the
            difference (SED) in consumption between concentration means for each
            time period and day are given.*

Day	Conc.	Time period (hr)				
		1	2	3	8	24
	L	45.5	57.9	64.3	84.6	93.7
1	M	38.0	48.9	56.9	83.6	89.3
	H	38.8	51.7	56.6	79.8	86.7
	SED	8.4	7.0	6.1	7.2	6.3
	L	18.9	34.7	45.1	77.7	83.0
2	M	13.0	22.0	35.4	69.7	73.6
	H	18.1	25.5	39.4	71.9	77.5
	SED	7.0	3.7	5.2	7.2	4.9
	L	19.7	35.6	44.5	70.3	76.3
3	M	26.0	35.9	44.3	74.8	83.0
	H	21.6	35.4	41.8	66.0	71.7
	SED	6.8	5.0	5.7	7.6	6.5
	L	20.8	36.6	45.0	67.8	82.0
4	M	18.3	26.2	35.6	52.9	67.7
	H	14.3	21.7	30.6	48.4	59.4
	SED	9.5	7.4	9.3	5.1	3.5

Experiment 2

No differences in wheat consumption were observed between sparrow populations that were experienced with repellents or naïve (P > 0.10). All of the plain wheat offered was consumed by sparrows every day during Experiment 2 (Figure 2), with $94.7 \pm 1.8\%$ of the plain wheat eaten in less than 3hr. At the 3hr wheat measurement, significantly less of the d-pulegone + Avex combination wheat had been consumed on average ($9.3 \pm 0.9\%$) than Avex alone wheat ($15.3 \pm 1.3\%$; $F_{1,6} = 11.46$, p = 0.015). Sparrows ate progressively less after 3hr over the 10-day exposure period ($F_{1,6} = 10.32$, $P = 0.019$). On average over the 10-day period, sparrows ate significantly less d-pulegone + Avex combination wheat at the 24hr measurement (25% of wheat offered), than wheat treated with Avex alone (45% of wheat offered, Figure 2; $F_{1,6} = 15.95$, $P = 0.007$). The difference in the wheat consumption of sparrows between repellent treatments was not significant on Day 1 ($P = 0.146$) and Day 10 ($P = 0.200$) of presentation, but was significant on all other days (P values for each day ranging from $P < 0.001$ to $P = 0.049$; Figure 2). Despite the appearance that the consumption of Avex alone-treated wheat declined over time (Figure 2), there was no significant time trend for changes in consumption of either type of repellent-treated wheat over the 10-day period ($P = 0.176$).

Discussion

Two of the repellents tested in the current study did not greatly reduce the house sparrows' propensity to eat hulled wheat. Previous researchers have found neem oil (Mason and Matthew, 1996) and agricultural lime (Belant *et al*, 1997; Clark and Belant, 1998) to be effective repellents for other bird species at similar concentrations. Several possibilities exist for why the repellents were not effective here. Firstly, the method we used to apply the repellents to wheat may have affected the repellent effects observed. For example, the repellent effect of agricultural lime is mediated partly by pH (pH higher than 12 is repellent; Belant *et al*, 1997), and our wheat may not have achieved this pH value). Secondly, our test methodology, in which sparrows were made familiar with the plain wheat, may have reduced the repellents' effectiveness. Repellents sometimes, but not always, work most effectively if the treated food is also novel (Greig-Smith, 1987). However, others
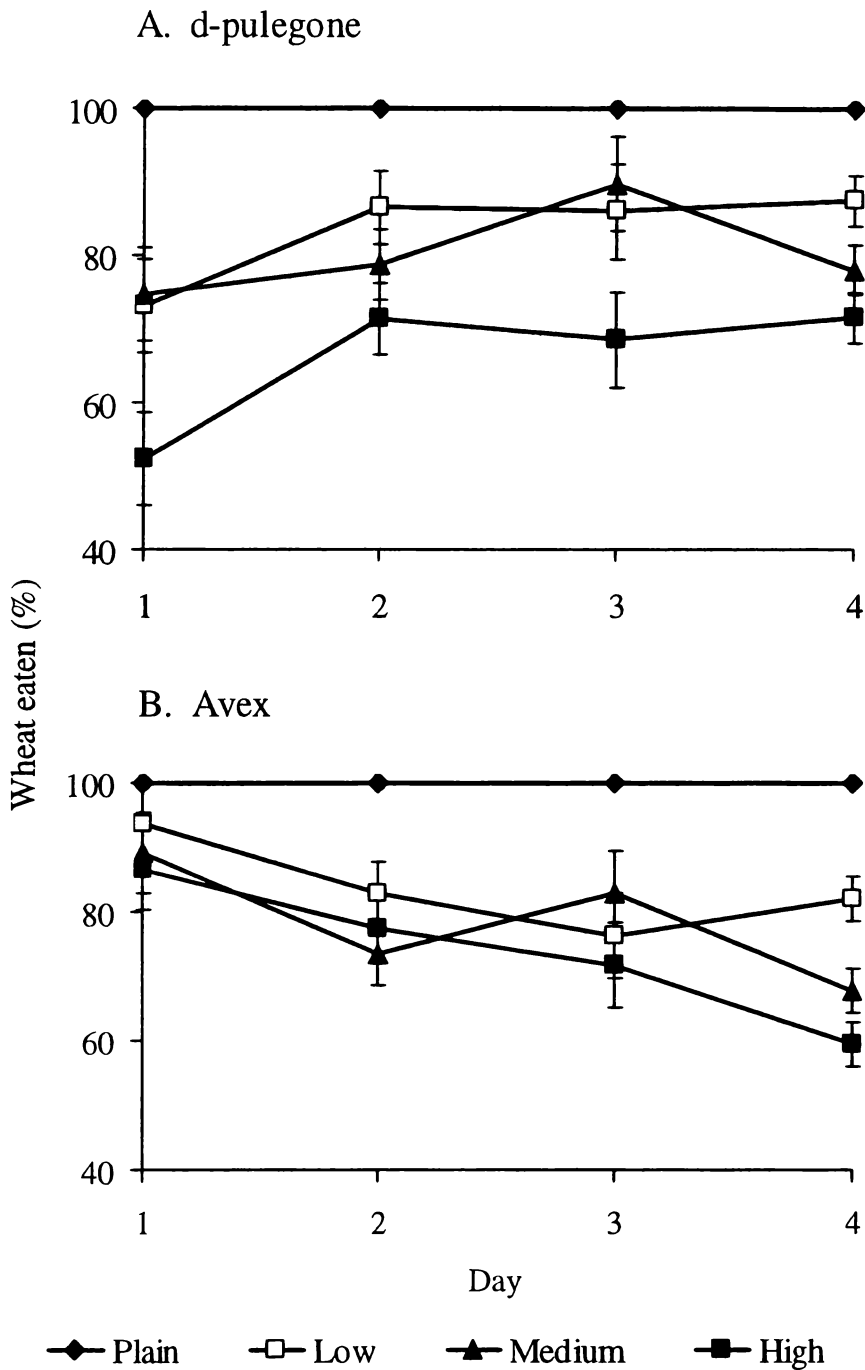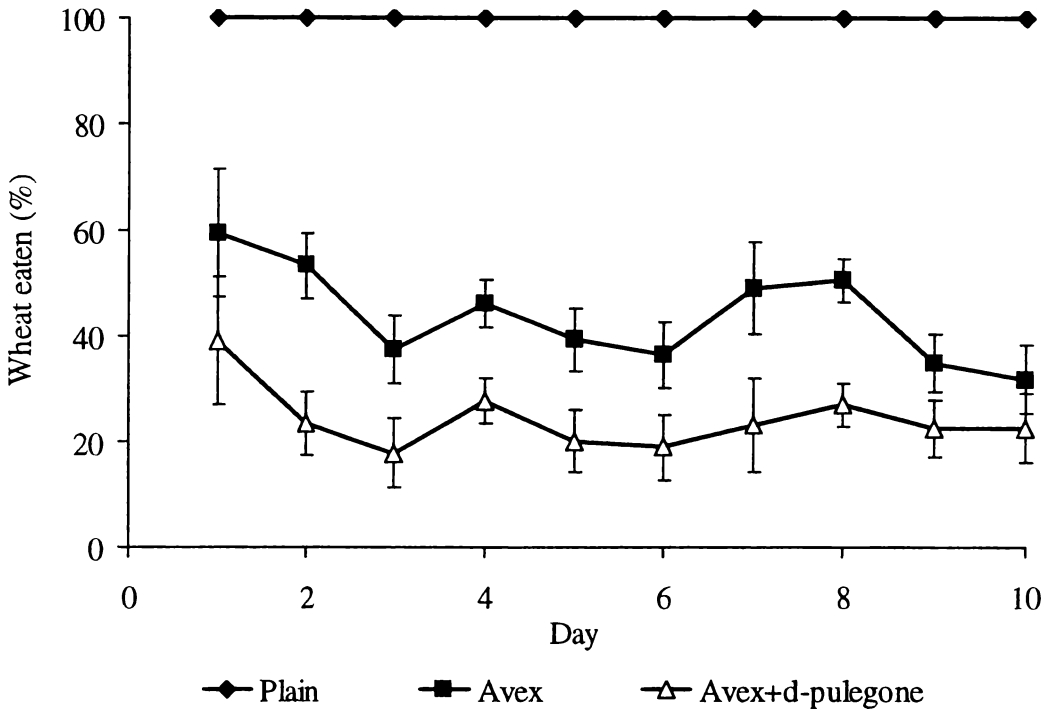
Figure 2:   *Mean (± SED) daily percentage of each wheat treatment eaten over the 10-day test period in Experiment 2 by sparrows offered a choice between plain wheat and one of two types of repellent-treated wheat: Avex alone (2% concentration) or d-pulegone (2%) + Avex (2%) in combination.*

have demonstrated the repellent effects of neem oil and lime using familiar foods (Belant *et al*, 1997; Mason and Matthew, 1996). Thirdly, there may have been strong competition among sparrows for access to the wheat, and therefore strong motivation to eat the repellent treatments. During the pre-treatment phase of this experiment, sparrows ate all of the plain wheat offered within two to three hours of presentation, suggesting they could easily have consumed much more over a 24hr period. During the treatment phase, the plain wheat on offer was quickly removed, leaving only repellent-treated wheat available thereafter. Due to competition, some birds may have found the repellent-treated wheat the only food they could access, or had to 'settle' for treated wheat when plain wheat became scarce. Additionally, house sparrows may be less sensitive to the effects of some repellents than other species. For example, sparrows were only repelled from methyl anthranilate after being exposed to eight times the concentration of repellent required to deter feral pigeons (*Columba livia*; Moran, 2001). Sparrows also continue to test and consume

some repellent-treated foods for many more exposures than other species (e.g. starlings; Greig-Smith and Rowney, 1987), so our four-day period may have been insufficient time to demonstrate repellency.

D-pulegone suppressed the wheat consumption of sparrows by nearly 50% from the first day of exposure, suggesting that d-pulegone acted as a primary repellent for sparrows. The level to which feeding was suppressed was similar throughout the four days of exposure. D-pulegone has previously been reported as a primary repellent and repels birds via taste and olfactory cues (Mason, 1990). It requires minimal or no consumption to cause avoidance (Wager-Page and Mason, 1996). In the current study, it is unlikely that d-pulegone caused any post-ingestional effects (and a subsequent learned avoidance), as there was no evidence of increased avoidance of d-pulegone-treated wheat over time. However, post-ingestional illness, including vomiting, has been observed in some birds after eating d-pulegone-treated food (Mason, 1990), so the possibility cannot be totally discounted.

In Experiment 1, Avex effectively deterred sparrows from feeding only after repeated days of exposure. The pattern of wheat consumption was consistent with previous research, which has found that birds exhibit learned aversions to anthraquinone-treated foods (Avery et al, 1997; Dolbeer et al, 1998). Wheat consumption was suppressed by up to 40% on Day 4 of exposure at the highest concentration, but a large quantity of wheat (60%) was still removed. Ideally, a repellent would almost entirely prevent birds from sampling the treated food, especially if the food was a valuable crop or was toxic to the birds. Most other studies have also found that anthraquinone does not completely eliminate feeding (Avery et al, 1997, 1998). In the current study, it is possible that the daily composition of the sparrow flocks varied, with new sparrows sampling the treated wheat for the first time on each of the test days, thereby giving rise to the continued consumption of treated food. If this were the case, however, we would have expected to see similar effects on consumption of the other wheat types.

The pattern of consumption of wheat treated with Avex alone differed between Experiments 1 and 2. In Experiment 1, a greater percentage of Avex alone-treated wheat was consumed on Day 1 (90%) than we observed on Day 1 in Experiment 2 (60%). Further, in Experiment 2, we did not observe a significant decrease in Avex alone-treated wheat consumption over repeated exposures, as was evident in

Experiment 1. Several possibilities exist for the observed difference between experiments. Firstly, in Experiment 2 we offered sparrows twice as much Avex alone-treated wheat as was presented in Experiment 1 (100g/day versus 50g/day). While sparrows ate a smaller percentage of Avex alone-treated wheat in Experiment 2 at first exposure, they actually consumed a similar mass of wheat ($45 \pm 2g$ in Experiment 1, $54 \pm 12g$ in Experiment 2). However, when twice as much plain wheat was also offered in Experiment 2, the sparrows readily consumed double the mass. Secondly, Experiment 2 was conducted eight weeks after the conclusion of Experiment 1, and used four of the same sparrow populations. It is possible that avoidance of Avex alone-treated wheat learned by sparrows in Experiment 1 was carried over to the beginning of Experiment 2. This would have decreased the consumption of wheat treated with Avex alone at first exposure in Experiment 2. However, four of the sparrow populations used in Experiment 2 were naïve to the Avex alone treatment, so these populations should not have avoided this treatment on Day 1. Despite this, we did not detect any differences in wheat consumption between naïve and experienced sparrow populations. The reduced percentage of Avex alone-treated wheat consumed may have been caused by differences in the sparrow population size, availability of alternative preferred foods during Experiment 2, or differences in climatic conditions that modified the level of wheat consumption by the populations.

The combination of 2% d-pulegone + 2% Avex suppressed wheat consumption by sparrows significantly more than when Avex was used alone. Overall, the combination resulted in less than 25% of treated wheat being consumed, compared to 45% of Avex only-treated wheat being removed. While Avex alone is a relatively effective repellent for sparrows (Experiment 1 and 2), it may lack a highly conspicuous associated cue that could aid avoidance learning. Odours, visual cues or other chemicals have been used successfully to enhance the speed of learning and overall effect of other secondary repellents (e.g. Avery and Mason, 1997; Avery and Nelms, 1990; Greig-Smith and Rowney, 1987; Nelms and Avery, 1997). We did not test for the relative roles of the two repellents when used in combination, but it is possible that d-pulegone, in addition to being aversive as a primary repellent, acted as a salient cue for a learned avoidance response caused by Avex. For example, if sparrows associated an Avex-conditioned avoidance response with the strong

peppermint odour of d-pulegone, birds could subsequently avoid treated food on the basis of odour alone. This may have led to the faster or greater avoidance response for the combination than was seen towards Avex alone. Combining two repellents with known primary and secondary modes of action reduced food consumption more rapidly than any other repellent, and shows great promise for deterring sparrows from feeding on treated food sources.

Birds often rely on sight rather than on their chemical senses for making feeding choices (Kare and Mason, 1985). Anthraquinone has been suggested to have associated ultraviolet visual cues which birds respond to (Ballinger, 1999, 2001), and this may have helped mediate the Avex alone avoidance response we observed in the current experiment. Blackwell *et al* (1999) found that a different anthraquinone-based repellent (Flight Control) was more effective on Canada geese when paired with an additional visual cue (novel colour). The avoidance by sparrows of blue-dyed food (Pawlina and Proulx, 1996) suggests that colour would be a useful additional or alternative cue for this species also. Avery (1997) suggested that repellent researchers should investigate complex multiple signals used in animal communication, such as predator-prey warning signals, to enhance repellents. However, any alternative combinations will need to be thoroughly tested, as employing multiple sensory cues may render some combinations ineffective based on the principles of concurrent interference and paired relevance (Sayre and Clark, 2001).

In the current study, we used free-ranging bird populations to assess the effect of repellents and did not measure the feeding behaviour of individual birds. We are confident, based on our video recordings, that sparrows rather than other avian species, accounted for almost all of the feed removals observed, but as we did not measure individual sparrow feeding behaviour we need to be cautious when interpreting differences in wheat consumption towards different repellents, or over time. For example, in Experiment 1 the response of each sparrow population towards Avex-treated wheat was initially to eat the wheat on Day 1 and then progressively reduce consumption over subsequent days. This pattern of consumption could have arisen from all of the individual sparrows sampling the wheat and then avoiding it over time, or from some birds continuing to eat repellent-treated wheat while others completely avoided the wheat after first encountering it. However, most individual

birds in flocks respond similarly to foods (Reidinger and Mason, 1983; Ward and Zahavi, 1973), so it is likely that most sparrows responded in a similar manner to each repellent. Additionally, whether experienced or naïve, the populations used in this study responded very similarly to each repellent, suggesting that individual birds were behaving consistently. For crop protection applications, it is the overall reduction in damage afforded by a repellent that is important, and our data clearly demonstrate changes in the overall feeding behaviour of sparrow populations.

Management implications

House sparrows decreased consumption of food treated with Avex, d-pulegone or the combination of both. Each repellent offers potential to deter sparrow populations from feeding, but the combination of primary and secondary repellents provides the most promise for achieving a rapid feeding suppression that is also long-lasting. Further research is required to determine efficacy and cost-effectiveness in the field as well as any phytotoxic or other effects the repellent combination could produce. For crop protection purposes, application techniques that do not diminish the value of the crop will be necessary, such as applying the repellent to only enough parts of the crop to allow avoidance learning to occur. Damage to crops is often caused by several bird species, so the efficacy of the repellents for preventing feeding in a range of other pest birds will be important.

A significant application for the use of combined primary and secondary repellents is the protection of non-target birds from accidental poisoning with pesticides. In New Zealand, birds of several native species die after eating pest control baits intended for mammalian pests (Spurr, 2000), and repellents have been proposed as one strategy to avoid poisoning. Furthermore, worldwide, granular pesticides are applied to millions of acres of crops and birds are at risk of being poisoned if they pick the granules up as a source of grit (Gionfriddo and Best, 1996). The repellent combination tested in the current study may provide the type of protection desirable in toxic bait. Birds would be initially deterred from the baits by primary repellent cues and, if they sampled some bait, would develop conditioned food aversions from the secondary repellent components. Additionally, pesticides are often dyed colours that deter birds (e.g. green or blue; Hartley *et al*, 2000) and this colour may act as an

additional cue for the formation of the conditioned response. However, to be suitable for pest control baits, the repellents must meet two main criteria. Firstly, the repellents should not compromise the efficacy of target pest control (Spurr *et al*, 2001), and secondly, the repellents should be able to deter a range of at-risk bird species, as different species vary widely in their responses to repellents (Greig-Smith and Rowney, 1987).

Acknowledgements

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Summary:

In this chapter (Chapter 2), I found that a primary repellent (d-pulegone) significantly reduced wheat consumption by sparrows at first exposure, with birds continuing to eat less d-pulegone-treated wheat throughout the four days. A secondary repellent (Avex) caused less reduction in wheat consumption than d-pulegone at first exposure, but sparrows ate progressively less Avex-treated wheat over each of the following days, suggesting a learned avoidance response. For both d-pulegone and Avex, there was a negative relationship between wheat consumption and repellent concentration. The combination of 2% d-pulegone + 2% Avex initially reduced daily wheat consumption significantly more than Avex alone and caused avoidance lasting throughout the 10-day test period. These results provided evidence for the enhanced rate of deterrence and longevity of effect gained by combining primary and secondary repellents with different modes of action.

In the next chapter (Chapter 3), I measure the feeding responses of North Island robins towards the same repellent combination (2% d-pulegone + 2% Avex) that successfully reduced food consumption by sparrows. Robins are a native New Zealand passerine that has been demonstrated to be at risk of poisoning during pest control operations targeting mammalian pests. Chapter 3 develops an appropriate method for testing the repellents and compares the feeding responses of robins towards two bait types: baits treated with either the repellent combination or standard New Zealand pest control baits (containing green dye and cinnamon oil).

Chapter 3

Repellents to deter New Zealand's North Island robin *Petroica australis longipes* from pest control baits

Tim D. Day, Lindsay R. Matthews and Joseph R. Waas

Abstract

North Island robins, (*Petroica australis longipes*), are among the non-target animals at risk during poisoning operations aimed at introduced mammalian pests in New Zealand. Adding an avian repellent to the bait may reduce the risk to native birds. In this study we report on two experiments that aimed to: (1) refine a methodology for testing repellents; and (2) determine the effects of a repellent combination on bird feeding behaviour. In Experiment 1, a highly preferred base material (in which repellents could be incorporated) was identified from the choices made when robins were presented simultaneously with cereal, carrot and dough materials over four consecutive days on a test arena on the forest floor. Robins pecked at and ate all materials, but consistently directed more pecks at dough ($P < 0.001$), so this material was selected for use in the subsequent study. In Experiment 2, robins were offered repellent-treated (green and surface coated with a combination of 2% d-pulegone and 2% Avex) and standard dough (green and coated with cinnamon oil; the bait formulation currently used for pest control operations in New Zealand) in choice tests over four days. The dough had either been sprayed with or dipped into the repellent combination. Robins pecked at standard dough more frequently than at repellent dough ($P < 0.05$), with the frequency of pecking at repellent dough declining ($P < 0.05$) over the four days. Male robins offered dipped dough pecked at the repellent dough more frequently than females. On occasions, the base material was removed from the arena by the birds: standard dough removed was consumed readily but repellent-treated dough was not. The results demonstrated that the combination of 2% d-pulegone + 2% Avex deterred

robins from feeding better than standard baits. Green dye and cinnamon oil did not appear to deter feeding on cereal, carrot or dough by robins, and thus can not be considered as effective repellents. Since a combination of d-pulegone + Avex was was effective in reducing feeding on a highly preferred base material, it is it is likely to reduce the propensity for robins to feed on toxic possum baits.

Introduction

Poisonous baits are used widely in New Zealand to kill introduced mammalian pests. Effective pest control operations have conservation benefits, including recovery of bird populations such as the North Island robin (*Petroica australis longipes*; Powlesland *et al*, 1999) and North Island kokako (*Callaeas cinera*; Innes *et al*, 1999). It is generally assumed that the benefits of pest control outweigh the risks to non-target species (Spurr, 1991).

  Poison-based pest control has caused some mortality of non-target native bird species (Spurr, 2000). Ground-feeding birds, such as the robin, are particularly vulnerable to poisoning (Brown, 1997; Empson and Miskelly, 1999; Powlesland *et al*, 1999). While there is currently no evidence of long-term adverse impacts of poisoning on populations of non-target species that have been adequately monitored, non-target mortality is a significant factor reducing the acceptability of pest poisoning operations to the public (Fitzgerald *et al*, 2000). Further, the possibility remains that there may be adverse effects on species that have not yet been assessed. By reducing non-target bird mortality during pest control, populations may recover more quickly and successfully and pest control practices may be considered to be more ethically sound.

  Two main bait manipulations are currently used to deter birds from eating toxic substances (as specified in the Pesticides Act, 1979): 1) all baits must be larger than 16mm, so small birds cannot readily manipulate them; and 2) all baits must be dyed green, a colour believed to be unattractive to birds (Caithness and Williams, 1971). Additionally, cinnamon oil is frequently added to bait to help deter birds. Unfortunately, native birds still die during pest control operations that use large,

green-dyed, cinnamon-flavoured baits (Spurr, 2000). Therefore, baits or bait additives are required that effectively repel non-target birds while remaining attractive to pest species such as brushtail possums (*Trichosurus vulpecula*) and rats (*Rattus* spp).

Potential methods for reducing bait acceptability to birds include the use of less-preferred bait types (e.g. gel bait; Morgan, 1999), less preferred bait colours (e.g. blue; Hartley *et al*, 1999; Hartley *et al*, 2000), or bird repellent compounds (e.g. cinnamamide; Spurr and Porter, 1998). Each of these has limitations. While gel baits appear to be unattractive to native birds (Morgan, 1999), to date they have not been used to control pests over the very large areas that can be effectively controlled with aerially sown baits. Additionally, some bait types (e.g. cereal) may pose greater risk to birds if the baits break up into edible-sized pieces when birds feed on them. Blue dye is less attractive to native birds than green (Hartley *et al*, 1999; Hartley *et al*, 2000), and is accepted by pests (Day and Matthews, 1999), but is not a long-lasting deterrent. Chemical repellents that have been tested to date are either too costly or have deleterious effects on bait consumption by target pests (e.g. cinnamamide; Spurr and Porter, 1998; Spurr, *et al*, 2001).

Repellents may be classified as either primary or secondary (Rogers, 1978). Primary repellents cause immediate rejection of a treated food through visual, olfactory, gustatory or irritant cues and require little or no learning to be effective (Clark, 1998). They do not usually promote long-lasting avoidance responses (Domjan, 1998), but may be more benign than secondary repellents. Secondary repellents act via an illness-induced learned avoidance of the treated food. The degree of avoidance depends on the strength of the unpleasant experience and the animals' ability to associate the illness with cues presented by the repellent food. Unfortunately, some secondary repellents have undesirable physiological and metabolic consequences (Sayre and Clark, 2001), and it may not be desirable to expose valued native species to such chemicals.

Combinations of repellent stimuli can be more effective for deterring birds than single repellents. Pairing a secondary repellent with either another chemical or a visual cue has been found to enhance the degree of repellency and the speed of avoidance learning (e.g. Mason and Reidinger, 1983). Also, secondary repellents are effective at much lower concentrations when paired with aversive primary repellents,

such as tastes, odours or colours (Avery and Mason, 1997; Avery and Nelms, 1990; Nelms and Avery, 1997).

The volatile compound d-pulegone (CAS No. 89-82-7; a type of peppermint) acts as a primary repellent for birds via both volatile cues (odour) and by direct contact (taste) (Wager-Page and Mason, 1996). It has been shown to repel several bird species at a 1% wt/wt concentration, including European starlings (*Sturnus vulgaris*; Mason, 1990) and northern bobwhites (*Colinus virginianus*; Mastrota and Mench, 1995). As d-pulegone repels birds without them having to ingest the food, the compound may be ideal for prevention of intake of poisonous baits. However, primary repellents often do not promote total or long-lasting avoidance responses when they are used alone (Domjan, 1998). Wild brushtail possums and rats readily take carrot baits containing d-pulegone (Day *et al*, 2000).

Avex (Loveland Industries Inc., USA) is an anthraquinone-based secondary repellent, and is commercially available in New Zealand. The product contains 9,10-anthraquinone (50% wt/wt; CAS No. 84-65-1) as the active ingredient. No peer-reviewed papers appear to have been published on Avex, although the active ingredient, anthraquinone, is a recognised avian feeding deterrent (Neff and Meanley, 1957) that operates via conditioned taste aversion. The repellent properties of anthraquinone and of a similar anthraquinone-based product, Flight Control (Environmental Biocontrol International, USA), have been rigorously evaluated with several bird species over recent years (e.g. Avery *et al*, 1998, 2001; Blackwell *et al*, 1999; Dolbeer *et al*, 1998). Baits treated with Avex are readily eaten by possums, and wild rodents readily take Avex-treated baits from bait stations (Day *et al*, 2000).

In Chapter 2, we found that the combination of 2% d-pulegone and 2% Avex was highly effective for deterring sparrows from feeding on wheat, and much more effective than either repellent used alone. Therefore, in the present study we sought to determine the efficacy of the same combination (2% d-pulegone and 2% Avex) for deterring the North Island robin from feeding. Robins are small (18cm, 35g), territorial, insectivorous forest passerines that feed predominantly on the forest floor (Heather and Robertson, 1996). They are particularly vulnerable to poisoning (Powlesland *et al*, 1999) and have previously been observed eating toxic cereal and carrot baits (Spurr and Powlesland, 1997). Also, wild robins are easily observed and have successfully been

used to measure bait colour preferences (e.g. Hartley *et al*, 1999), making them an ideal species for evaluating repellents in the context of pest control in New Zealand.

   The current study had two aims. Firstly, we aimed to identify a preferred base material that robins would peck at and eat (Experiment 1). We chose to identify and use a preferred base material for the repellency studies to create a conservative test of any repellent effects. Evidence from poisoning operations suggested that robins eat the typical cereal- or carrot-based toxic baits (or bait fragments known as 'chaff') (Powlesland *et al*, 1999) and Hartley *et al* (1999) successfully used a flour/lard-based dough to test colour preferences in robins. Secondly, we aimed to use the preferred base material to determine the efficacy of the combination of d-pulegone and Avex for deterring robins from feeding (Experiment 2), using two methods of applying the repellents to the base material. We used choice tests to enable us to compare the efficacy of the repellent combination to the efficacy of standard baits (green and cinnamon) currently used for pest control in New Zealand.

Methods
The experimental protocols were approved by an independent Animal Ethics Committee (Ruakura AEC approval 3136).

Experiment 1
In this experiment we determined robins' preference for cereal (RS 5 cereal, Animal Control Products Ltd, Waimate), carrot and dough (flour, water, lard, sugar, and green dye cooked for 15 min at 150°C) base materials. All base materials contained, or were coated with, green dye (0.01% Special Green V200A dye, Bayer NZ Ltd, Auckland) and cinnamon oil (0.1% wt/wt, Bush Boake Allen Ltd, Auckland), as is standard practice with possum baits used in the wildfor control in New Zealand. The three base types were all non-toxic.

Birds   Twelve wild robins (five female, seven male) living on Tiritiri Matangi Island (36°36' S, 174°53'E, Hauraki Gulf, New Zealand) were used in this study during the austral winter (June 2000). Each bird had previously been identified with a unique combination of leg bands for population monitoring purposes and the

territories of the birds were known (Armstrong *et al*, 2000). All birds were at least one year old and had previously been trained to approach an observer to receive mealworm (*Tenebrio molitor*) larvae. Eight of the birds lived and were tested in exclusive territories and four birds (two male-female pairs) lived in shared territories with their mates.

Test procedure   We modified the method of Hartley *et al* (1999) to offer the robins choices of different base materials. A test arena, consisting of a 0.75 m x 0.50 m area scraped clear of leaf litter, was set up centrally in each robin territory each day. Robins were attracted to the test arena by the observer tapping with a finger on a plastic container. Once the robins were within three metres, small twigs were tossed into the test arena. This stimulated the robins to alight in the arena and eat invertebrates and investigate the base materials. Robins showed considerable interest in the test arena, as clearing the leaf litter exposed invertebrates that the robins foraged for.

Robins were offered, for four consecutive days, a choice between the three types of base material in the test arena for 25 minutes (between 0700 h and 1600 h each day). All three materials were chopped into approximately 5mm cubes, a size which could be readily manipulated by robins. A teaspoon of each bait type (~20 g) was placed in a row in the middle of the test arena, with each base material 25 cm apart. The position of each material on the arena was moved in a randomised order for each bird each day.

We used a video camera (Sony TRV310E Digital Handycam) to record the feeding behaviour of each robin during the 25-minute test. The camera was mounted on a tripod 1.5m above the ground and was positioned 2-3m from the arena. The raw data were transferred to VHS tape for analysis. In subsequent analyses of the videotapes, every peck directed towards the three base materials was recorded (using slow-motion playback where necessary). A peck was defined as every contact made by the robin's beak with one of the base materials. Two observers were used to analyse the video tapes. To calculate inter-observer reliability, both observers recorded the pecking behaviour of robins from 10 randomly chosen test sessions. The inter-observer reliability for the peck frequency (expressed as the Pearson correlation coefficient) was $r = 0.94$ ($n = 10$, 8 d.f.). If a robin removed one of the base materials

from the test arena (i.e. picked it up in its bill and flew away with it), the type of base material removed (cereal, carrot or dough) and the subsequent fate of the base material (eaten, dropped or taken out of sight) was recorded.

Experiment 2

In this experiment we aimed to determine the effect of repellent treatment on feeding behaviour when offered a choice between repellent-treated dough (green and surface coated with a combination of 2% d-pulegone and 2% Avex) and a standard dough (green and containing 0.1% cinnamon). Dough was selected as base material for this experiment as results from Experiment 1 indicated that it was the most highly preferred base material. We used dough containing green dye and cinnamon oil as our standard for comparison, as this combination of colour and odour is routinely used on baits during normal pest control operations. Using a choice-test, this enabled us to compare the repellent (d-pulegone and Avex) with the method currently used to deter birds (green dye and cinnamon oil). Two methods of applying the repellents to the surface of the dough were used: "spraying" and "dipping".

Birds

Birds offered "sprayed" (see below) dough: Seventeen wild robins (eight female, nine male) were used in austral winter 2000, two weeks after Experiment 1 had concluded. Thirteen of the birds lived and were tested in exclusive territories and four birds (two male-female pairs) lived in shared territories with their mates. Each bird had been uniquely identified with leg bands and all birds were at least one year old. The robins had previously been trained to approach an observer to receive mealworms and 10 (five female, five male) of the robins used in this experiment had been exposed to the base materials in Experiment 1.

Birds offered "dipped" (see below) dough: Twenty-one wild robins (four females, 10 males and seven birds of unknown gender) were used in this experiment, two weeks after the first part of Experiment 2 (using sprayed dough) had been completed (July 2000). Ten of the robins had been exposed to the base materials and the experimental procedure in either Experiment 1 or the first part of Experiment 2.

Test procedure We used the same method as in Experiment 1 to offer the robins choices of repellent-treated or standard dough. A test arena was set up centrally in each robin territory each day. Robins were then offered, for four consecutive days, a choice between repellent or standard green-dyed (0.01% Special Green V200A dye, Bayer NZ Ltd, Auckland) dough in the test arena for 25 minutes (between 0700 h and 1600 h each day). All dough of both types was chopped into approximately 5mm cubes so that the robins could readily manipulate them. A teaspoon of each dough type was placed 25cm apart on the test arena and the positions of the repellent and standard dough were randomised for each bird and then alternated each day.

The green-dyed repellent dough was treated with a solution of water containing 2% (wt/wt) Avex (50% wt/wt 9,10-anthraquinone; CAS No. 84-65-1) and 2% d-pulegone (85% tech., CAS No. 89-82-7; Aldrich Chemical Co., USA). The dough was treated with repellent by either: (1) "spraying" the solution onto the surface of the dough (at a rate of 10% (wt/wt) of total bait weight) using a fine mist sprayer 36 hr prior to the experiment and stored them in airtight containers; or (2) "dipping" the chopped dough into the same volume of treatment solution in sieves 36hr prior to the experiment and then allowing the dough to air-dry before sealing them in airtight containers. The green-dyed standard dough was surface coated with a solution of water + 0.1% cinnamon oil using the same application techniques as for the repellent baits.

Robins were attracted to the test arena by the observer tapping on one of the dough containers. Once the robins were close, small twigs were tossed into the test arena to attract the robins. The feeding behaviour of each robin was recorded with a video camera (using the same method we employed in Experiment 1) and every peck directed towards either bait was subsequently determined from the videotapes. Again, inter-observer reliabilities were calculated for the two observers that analysed the pecking frequencies from the video tapes. From 10 randomly chosen test sessions, the inter-observer reliability for the peck frequency (expressed as the Pearson correlation coefficient) was $r = 0.96$ (n = 10, 8 d.f.). If a robin removed dough from the test arena, the type of dough removed and the subsequent fate of the dough was recorded. On the fourth day of dough presentation poor weather prevented us from collecting any data from the robins offered sprayed dough.

Data analysis (Experiments 1 and 2)

The number of pecks made at the different base materials from all experiments were analysed as Poisson variates using the General Linear Mixed Model (GLMM) in the Genstat 5.4 statistical package. The fixed effects we considered were base material type, day of exposure, time of exposure, bird gender and their interactions. Terms were retained for analysis when the related Wald statistic in GLMM gave a Chi-square value corresponding to $P < 0.05$. Sources of variation considered for the random model comprised bird location, base material position on the test arena and whether the robin was naive or experienced in the experimental procedure. Means were back-transformed from the Poisson model. To allow for low degrees of freedom on the error sources, approximate F-tests were used to determine the significance of differences between means. The number of pieces of base material of each type removed (and their subsequent fates) was compared using Chi-square tests.

Results

Experiment 1

On Day 1, all robins pecked at one or more of the three base materials. Although all base materials were pecked at, robins pecked significantly more at cereal and dough than at carrots ($P < 0.001$; Figure 1). The pecking frequency towards carrot baits remained low over all subsequent exposures. The frequency of pecking at cereal declined during Days 1 to 4 ($P < 0.01$) and the frequency of pecking at dough remained relatively constant ($P > 0.05$; Figure 1).

The frequency of base material removal did not significantly differ between bait treatments (see Totals, Table 1). Robins removed all three base materials from the test arena and, when it could be determined, usually ate the base material they removed (Table 1). There were no significant differences between the number of pieces of each material eaten or dropped (Table 1: χ^2 (4 d.f.) = 0.94, $P = 0.75$). Of the 41 removals recorded, 16 occurred on Day 1.
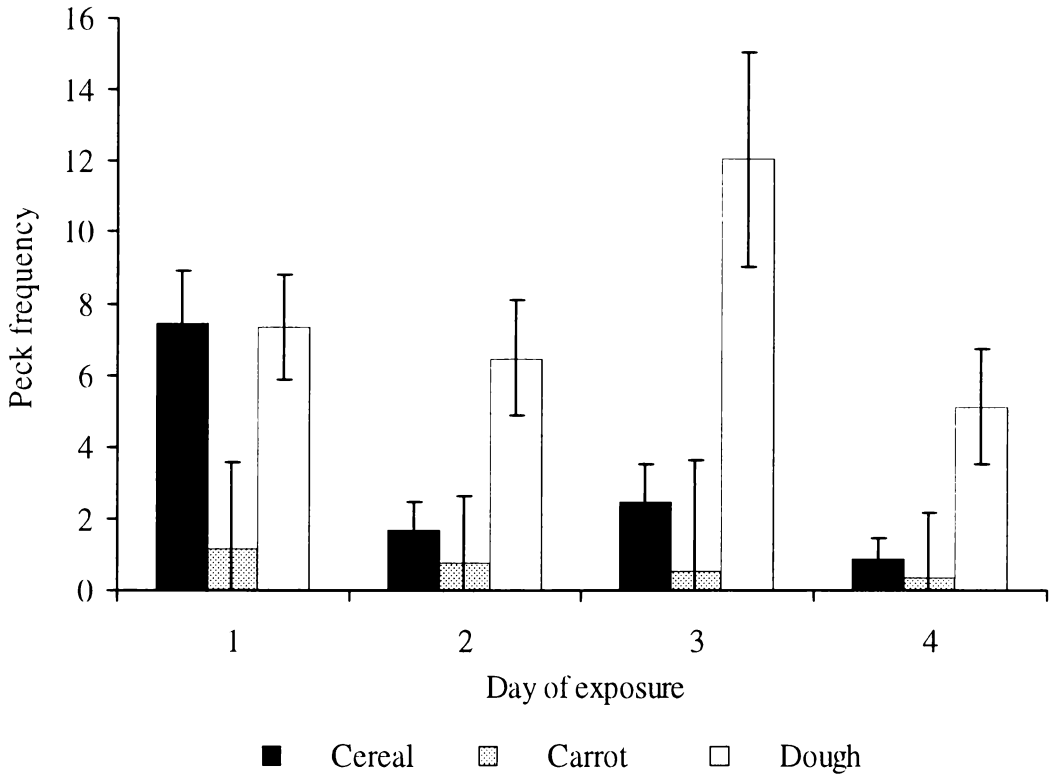
Figure 1:   *Adjusted mean number of pecks (±SE) by robins directed at cereal, carrot and dough at first and subsequent exposures in Experiment 1.*

Table 1:   *Number of pieces of base material removed from the test area by robins during all exposures and fate of the materials when removed in Experiment 1.*

Fate of material	Cereal	Carrot	Dough
Eaten	6	4	7
Dropped	1	1	0
Unknown	7	7	8
Total	14	12	15

Based on the pecking frequency over all days, and since there was no difference in removal behaviour, dough was chosen as the preferred base material with which to test repellents in Experiment 2.

Experiment 2

The peck frequency for repellent and standard sprayed dough is shown in Figure 2a; the result for repellent and standard dipped material is shown in Figure 2b. With both methods of application, repellent- treated dough was pecked less than standard dough.

a) Sprayed dough
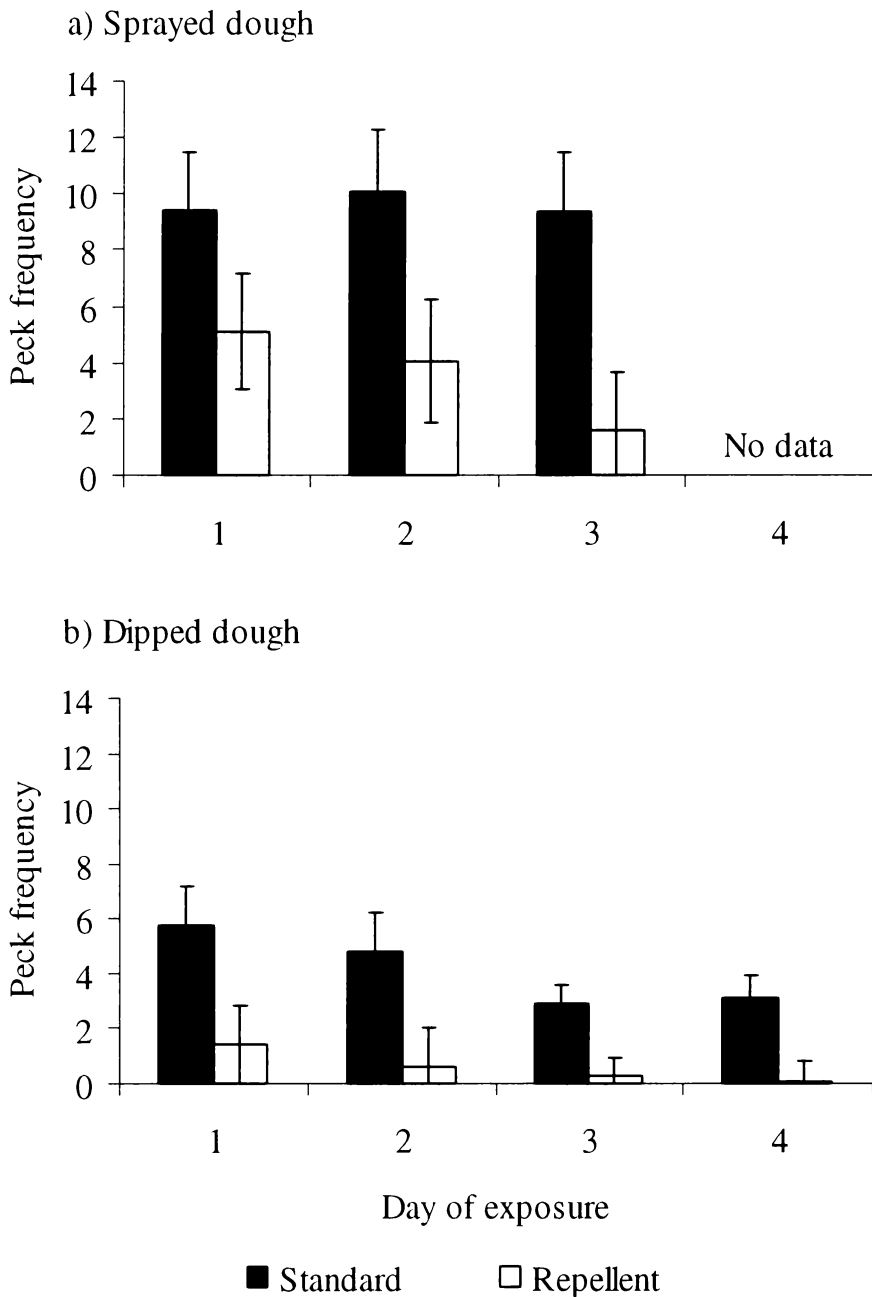
b) Dipped dough

Figure 2:   *Adjusted mean number of pecks (±SE) by robins directed at standard or repellent-treated dough at first and subsequent exposures in Experiment 2, for a) sprayed dough,; and b) dipped dough.*

On Day 1, all robins that were offered sprayed dough came on to the test arena and pecked at one or both of the dough types during the 25-minute test session. Overall, robins pecked at standard dough more frequently than they pecked at repellent dough ($P < 0.05$; Figure 2a), but they did make a number of pecks at repellent-treated dough. The frequency of pecking at the repellent-treated dough tended to decline over subsequent exposures, relative to the frequency of pecking at the standard dough, which remained constant ($P = 0.06$; Figure 2a). There were no significant differences in pecking behaviour towards the dough types between the genders ($P > 0.1$), or between naive or experienced robins ($P > 0.1$).

Dough removal differed between the sprayed treatments. Robins removed standard dough from the test arena more frequently than they removed repellent dough (Table 2), and tended to eat standard dough when they removed it. In contrast, the robins did not eat repellent-treated dough when they removed it from the test arena (Table 2; χ^2 (2 d.f.) = 23.0, $P < 0.001$). Of the 52 removals recorded, 30 occurred on Day 1.

Table 2:   *Number of sprayed pieces of dough removed from the test area by robins during all exposures and fate of the dough when removed in Experiment 2.*

Fate of dough	Standard	Repellent
Eaten	16	0
Dropped	0	8
Unknown	16	12
Total	32	20

The patterns of pecking and dough removal for robins exposed to dough treated by dipping were very similar to those reported for robins exposed to sprayed dough. On Day 1, all robins came on to the test arena, but five naive birds did not peck at either dough type during the first test session. The robins that did peck, pecked at standard dough more frequently than they pecked at repellent dough during the first and subsequent exposures ($P < 0.01$; Figure 2b). There was a significant interaction

between dough type and gender, with males tending to peck at repellent-treated dough more readily than females or robins for which we were unable to determine the gender ($P < 0.05$). The frequency of pecking at the repellent-treated dough declined significantly over the four days, relative to the frequency of pecking at the standard dough ($P < 0.05$; Figure 2b). There were no significant differences between naive and experienced robins in pecking behaviour towards either dough treatment ($P > 0.1$).

Dough removal differed between dipped-dough treatments. Robins removed dipped standard dough from the test arena more frequently than they removed repellent dough (Table 3), and tended to eat standard dough when they removed it. In contrast, the robins did not eat repellent-treated dough when they removed it (Table 3; χ^2 (2 d.f.) = 10.4, $P < 0.01$). Of the 41 removals recorded, 20 occurred on Day 1. Overall, less dipped dough was removed by robins than sprayed dough (41 versus 52 removals), despite the fact that more birds were tested over a greater number of days with the dipped material.

Table 3:   *Number of dipped pieces of dough removed from the test area by robins during all exposures and fate of the dough when removed in Experiment 2.*

Fate of dough	Standard	Repellent
Eaten	7	0
Dropped	2	6
Unknown	19	7
Total	28	13

Discussion

In Experiment 1, we offered robins three different base materials, two of which (cereal and carrot) are used routinely for possum control in New Zealand. Robins readily pecked at and ate all three, even though they contained green dye and

cinnamon oil. This observation is consistent with the finding that robins are occasionally poisoned during aerial control operations using green, cinnamon-flavoured cereal or carrot toxic baits (Brown, 1997; Empson and Miskelly, 1999; Powlesland *et al*, 1999). While green-dyed and cinnamon-flavoured baits may help protect some birds from poisoning, it is clear that robins, and other bird species, will sometimes sample and eat these baits. Carrot was pecked at least frequently by robins. This is most likely because carrot did not break into smaller edible fragments in the same way as cereal or dough. Robins readily pecked at and ate the small fragments of cereal and dough that broke off when they pecked at these materials. During a control operation, the risk of poisoning small forest birds may be increased for any toxic bait that breaks into edible fragments. Bait fragmentation could occur at any stage of preparation (e.g. poor sieving of carrot baits), distribution (e.g. bait breakage caused by the hoppers used to sow aerial baits) or exploration by birds (e.g. pecking). Therefore, large baits that are not readily fragmented during preparation, distribution, or exploration by non-targets should be used to increase bird safety.

The pecking behaviour of robins towards sprayed or dipped dough in Experiment 2 was similar. This suggests that the method of applying the repellents to the surface of the dough (spraying or dipping) did not greatly affect the way in which the repellents appeared to the robins. From a practical viewpoint, either method of applying the repellents to the surface of bait could be used during a pest control operation.

When offered a choice between standard and repellent-treated dough, robins pecked at repellent-treated dough infrequently when they were first offered it, and less frequently than they pecked at standard dough. This reluctance to peck at repellent dough at first exposure may have been a neophobic response towards a novel food or may have been caused by the innately aversive primary repellent (d-pulegone). Neophobia is an unlikely explanation for the initial avoidance of repellent dough however, as there was little evidence of an initial avoidance of the standard dough, which was also novel. Foods treated with d-pulegone are aversive repellent to some other bird species because of their odour, without any need for the birds to taste the food (Wager-Page and Mason, 1996).

The frequency of pecking at repellent-treated dough tended to decline over subsequent exposures in both experiments, while the frequency of pecking at standard dough did not. The decrease in pecking frequency towards repellent dough over time

suggests that the robins developed a strong learned avoidance response after they had sampled the dough. Other anthraquinone-based products (e.g. Flight Control) also readily elicit learned avoidance responses in birds typical of secondary repellents (Avery *et al*, 1997).

   The combination of d-pulegone and + Avex on dough appeared to have some primary and secondary repellency characteristics for robins. We did not test for the relative roles of the two repellents we used in these experiments, but it is possible that d-pulegone (a strong odour), in addition to being innately aversive, acted as a salient cue for the learned avoidance response caused by Avex. The combination of a primary and secondary repellent in baits (in this case a strong odour and taste, coupled with post-ingestional effects) may be ideal for preventing bait sampling over an extended period. The primary repellent would provide the birds with initial bait avoidance cues that prevent them from being poisoned. If the birds did sample a small amount of the bait the secondary repellent would then provide a learned avoidance response. In Chapter 2, sparrows were effectively deterred by this combination of repellents.

   The level of pecking response we observed in these experiments may have led to some robin deaths had the dough been toxic. We calculated theoretical poisoning thresholds, in terms of number of pecks, for robins exposed to toxic baits containing 1080 (sodium monoflouroacetate), the most commonly used pest toxin in New Zealand. The thresholds were calculated for baits containing 1080 at two concentrations that are typically used during poisoning operations (0.08% and 0.15% wt/wt). Lloyd and McQueen's (2000) estimate of 1080 LD_{50} values for robins were used. Robins would need to eat approximately eight dough fragments to exceed the threshold for receiving an LD_{50} dose of 1080 at 0.08% concentration. At 0.15% concentration they would only need to peck at and eat four fragments (0.16 g of dough) to exceed the threshold. In Experiment 2 the proportion of tested robins that would have been lethally poisoned by dough if they had contained toxin was then determined. Thirty percent of robins ate sufficient repellent-dough fragments to exceed the 0.08% 1080 poisoning threshold, and 53% exceeded the 0.15% threshold. For standard dough, 53% of robins were over the poisoning threshold for 0.08% concentration, and 65% were over the 0.15% threshold. While robins are less likely to peck at and eat cereal or carrot bait than the preferred dough we used in

Experiment 2, these data highlight how little a robin may need to eat to be killed during an aerial poisoning operation. The efficacy of repellents would be enhanced further if the pest control baits were already of low palatability to birds.

One way to maximise the effect of repellents on bird safety would be to provide repellent-treated non-toxic bait to birds prior to exposing them to toxic baits. This would allow the birds to safely sample and learn to avoid baits before they were toxic. Pre-feeding pest populations with non-toxic bait prior to toxic baiting is recommended in New Zealand to maximise pest kills (e.g. Moss *et al*, 1998). Repellents could readily be incorporated into the non-toxic prefeed.

In both experiments, robins removed more standard dough from the test area than repellent-treated dough. When we were able to determine what the robins did with the dough, we found that they generally ate the standard dough and dropped the repellent-treated dough. This result is particularly encouraging and suggests that the repellent not only reduced sampling, but also reduced ingestion, even on a preferred food (dough). In Experiment 2 however, we found that male robins were more prepared to peck at repellent-treated dough than females. Male robins routinely feed their mates and offspring in the breeding season (Armstrong *et al*, 2000), and it is possible that they are more prepared to thoroughly test a range of potential food sources than females. The significance of this finding in terms of robin poisoning in the wild is unknown and further research on the response of males during the breeding season is warranted.

Critical to the success of any repellent-treated bait, will be the bait's ability to prevent bird deaths while maintaining high pest kill rates. To achieve this, the bird repellents must not deter target animals (e.g. brushtail possums and rodent species) from eating baits. Day *et al* (2000) found that wild possums and rats take carrot baits treated with the combination of d-pulegone + Avex from bait stations as readily as they take standard (green, cinnamon-flavoured) baits, but the study used non-toxic baits and, therefore, did not confirm that the target pests would have been killed by the baits. Further research exploring the ability of repellent-treated baits to kill target pests is currently being conducted with captive rats and possums. Ultimately, the efficacy of repellent-treated baits will need to be tested and compared to standard baits in a range of field conditions, using different bait types (Day *et al*, 2000).

The results of the current research are promising, with the combination of a primary and secondary repellent effectively reducing feeding by most robins. Further research is needed to determine whether robins would eat repellent baits if they are offered them in no-choice situations or during the breeding season when they are feeding dependents. The most cost-effective way to incorporate effective combinations of repellents into baits should also be determined. For example, pairings of lowly preferred colours (e.g. blue; Hartley *et al*, 1999, 2000) with secondary repellents may be more cost-effective than using strong aversive odours, which tend to be more expensive. The efficacy of the repellents for deterring other bird species with similar and different feeding styles will also need to be determined. In addition, the efficacy of the repellent-treated baits for controlling target pests needs to be confirmed under the varied conditions encountered during normal pest control operations.

Acknowledgements

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Summary:

In this chapter (Chapter 3), I found North Island robins preferred pecking at dough baits over cereal or carrot baits. When offered a choice between standard and repellent dough baits, robins pecked at and removed the standard baits more frequently than the repellent-treated baits. These results demonstrated that the combination of a primary and secondary repellent (2% d-pulegone + 2% Avex) effectively deterred robins from feeding, a result consistent with my findings using sparrows in Chapter 2. Green dye and cinnamon oil (as are currently used in standard pest control baits) did not reduce to the same level feeding on cereal, carrot or dough by robins, and thus can not be considered as effective repellents.

In the following chapter (Chapter 4), I use sparrows, previously used in Chapter 2, to further explore how alternative combinations of primary and secondary repellents with different cues associated with them may be used to repel birds. The repellent combination used in Chapters 2 and 3 consisted of 2% d-pulegone (containing aversive olfactory and taste cues) and 2% Avex (acting primarily via post-ingestional illness). In Chapter 4, I compare the feeding responses of sparrows to wheat treated with 2% Avex, paired with either a novel visual cue (blue colour), cinnamon oil (containing primarily olfactory cues), or d-pulegone (containing olfactory and taste cues). This experiment was aimed at determining whether alternative combinations of cues are also effective bird repellents.

Chapter 4

Designer repellents: combining olfactory, visual or taste cues with a secondary repellent to deter free-ranging house sparrows from feeding

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Abstract

The feeding behaviour of free-ranging house sparrows (*Passer domesticus*) presented with wheat treated with the secondary repellent Avex (an anthraquinone-based product), paired with either a novel visual cue (blue colour), cinnamon oil (containing primarily olfactory cues), or d-pulegone (containing olfactory and taste cues), was recorded, to determine the suitability of repellent combinations for deterring non-target birds from consuming pesticides or other harmful substances. Eight independent populations of house sparrows in Hawke's Bay, New Zealand, were trained to eat plain hulled wheat from four identical food trays on feed tables. In Experiment 1, sparrows were presented, for four-day periods, with a choice between plain wheat, 2% Avex-treated wheat, and two of the remaining repellent combinations (cinnamon oil + 2% Avex, blue colour + 2% Avex, d-pulegone (at 0.5% or 2.0% concentrations) + 2% Avex) until all sparrow populations had been exposed to each repellent. The consumption of plain wheat and Avex-treated wheat was compared to the consumption of the repellent combinations every 24hr. Plain wheat was almost always fully consumed at each table each day; over the same timeframe, Avex alone significantly reduced ($P < 0.001$) wheat consumption, to 54% of that offered. Addition of cinnamon oil to wheat with Avex did not further reduce ($P > 0.10$) consumption (41%), but when Avex was paired with either blue colour or d-pulegone (either concentration), repellency was enhanced ($P < 0.01$). The combinations of 2% d-pulegone + 2% Avex or blue colour + 2% Avex elicited

the most effective avoidance responses (14.6% and 9.6% consumption, respectively; $P > 0.50$). No significant time trends were evident in wheat consumption over the four-day periods. In Experiment 2 the same populations and food tables were used to compare the consumption of plain wheat to that of wheat treated with either blue colour + 2% Avex, blue colour alone, or green colour alone on each table. The experiment was designed to evaluate whether blue alone was as effective as blue + 2% Avex for deterring sparrows. An eight day period was used to determine whether repellent effects lasted longer than the four days tested in Experiment 1. While sparrows ate all plain wheat that was offered every day, they initially avoided all three treated wheat types. Over time, sparrows progressively consumed more green and blue wheat that lacked Avex each day, eating significantly ($P < 0.05$) more of these treatments than blue + Avex by Day 5. Overall, green wheat was consumed more readily (47.5%) than blue wheat (35.3%; $P < 0.05$) or blue + 2% Avex wheat (14.7%; $P < 0.01$). Colour alone did not provide a long-lasting avoidance response in sparrows. These data clearly demonstrate the potential of combining Avex with additional visual, olfactory or taste cues for modifying the feeding behaviour of sparrows, and provide further evidence for the enhanced efficacy that may be gained by combining appropriate salient cues or primary repellents with secondary repellents.

Keywords: anthraquinone; Avex; bird repellent; colour; d-pulegone; feeding behaviour; house sparrow; odour; *Passer domesticus*.

Introduction

Repellents offer the potential to prevent bird pests from eating crops or to protect non-target birds from eating pesticides or other harmful substances (Clark, 1998b). Where the aim is to prevent birds from eating pesticide baits, repellents must cause rapid and long-lasting avoidance of the toxic food. Repellents have either primary or secondary modes of action (Rogers, 1978). Primary repellents consist of aversive visual, olfactory, taste or tactile cues (Clark, 1998a). They invoke instantaneous rejection responses, but do not usually promote long-lasting avoidance (Domjan, 1998).

Repellents with only a primary mode of action pose a risk of poisoning to birds that habituate to their effects. Secondary repellents produce an illness-induced learned avoidance of the treated food, but require ingestion of some treated food before learning can occur (Clark, 1998a). Accidental poisoning will arise if avoidance learning does not occur before the bird has consumed a lethal quantity of the treated food.

Combinations of primary and secondary repellent stimuli may be more effective at deterring birds than single repellents. Several researchers have found that addition of a visual cue enhances avoidance learning towards secondary repellents (Greig-Smith and Rowney, 1987; Mason and Reidinger, 1983). Avian colour vision is highly developed and in most species is the primary cue used for making feeding decisions (Avery, 1997). Addition of a novel odour cue can also enhance avoidance learning in birds (e.g. Roper and Marples, 1997), but some odours appear to be less effective for enhancing avoidance learning towards secondary repellents than visual cues (Mason and Reidinger, 1983) or tastes (Beauchamp, 1997). However, 'warning odours', such as methyl pyrazines used in insect defence against predators, can enhance and elicit strong avoidance responses when paired with other novel primary repellent cues in a food, such as colour (Guilford et al, 1987; Marples and Roper, 1996; Rowe and Guilford, 1996). The most effective cues are usually those with high detectability, discriminability and memorability for the target animal (Guilford and Dawkins; 1991). Combinations of repellents with salient olfactory, visual or taste cues may be highly effective (Avery and Mason, 1997; Nelms and Avery, 1997; Sayre and Clark, 2001).

The sensory capabilities of many bird species are still being defined, particularly in the area of avian olfaction (Avery, 1997). Recent research indicates that the olfactory ability of many avian species is well developed (Clark et al, 1993), with some species readily modifying their feeding behaviour in response to olfactory cues, such as pyrazine odour (Avery and Nelms, 1990), volatile d-pulegone (Wager-Page and Mason, 1996) and almond (Roper and Marples, 1997). The sensitivity of some bird species to olfactory cues may make such cues suitable for incorporation into "designer repellents". Avian colour vision is sophisticated and there is already ample experimental evidence that visual cues enable many bird species to discriminate between palatable and repellent foods (e.g. Avery and Mason, 1997; Mason and Reidinger, 1983; Nelms and Avery, 1997). Visual cues are an obvious possibility for

effective avian repellent design. Because birds are highly sensitive to both olfactory (Avery and Nelms, 1990; Clark *et al*, 1993; Wager-Page and Mason, 1996) and visual stimuli (Avery, 1997; Bowmaker *et al*, 1997), and because both visual and olfactory cues may act as primary repellents without any need for food sampling, both may be suitable for preventing birds from feeding on pesticide baits.

Free-ranging house sparrows (*Passer domesticus*) were chosen for this study as they are abundant in New Zealand, are non-migratory, and wild birds can readily be trained to use feed tables (Porter, 1997). They are also economic bird pests in New Zealand, because of the serious damage they cause to crops (Heather and Robertson, 1996; Porter, 1977; Porter *et al*, 1994). Additionally, house sparrows readily consume granular pesticides, putting them at risk of accidental poisoning (Gionfriddo and Best, 1996; Pawlina and Proulx, 1996). Sparrows are hard to deter from feeding (Porter *et al*, 1994), so make a good model bird for testing the efficacy of repellents. The relative scarcity of seed-eating species in urban and rural New Zealand habitats compared to the many species found in Europe and the USA (Heather and Robertson, 1996), means that experiments involving feed tables open to free-ranging birds will attract virtually only sparrows.

The effects of several repellents on the feeding behaviour of house sparrows have been investigated previously. Sparrows avoid familiar or novel food sources treated with chemicals reported as primary repellents, such as quinine sulphate, tannic acid, Optamint, d-pulegone and cinnamamide (Chapter 2; Greig-Smith, 1987; Moran, 2001; Porter, 1997). These chemicals act via aversive olfactory, visual or taste cues. Sparrows also assess foods on the basis of visual cues, avoiding black or blue food, and preferring to eat red, yellow or white foods (Gionfriddo and Best, 1996; Greig-Smith and Rowney, 1987; Pawlina and Proulx, 1996). Additionally, secondary repellents, such as methiocarb or Avex cause learned avoidance by sparrows (Chapter 2; Greig-Smith and Rowney, 1987; Porter, 1977). In Chapter 2, we found that the combination of 2% d-pulegone (olfactory and taste cues) and 2% Avex was highly effective at deterring free ranging house sparrows from feeding on wheat. Alternative combinations of cues, which target the visual abilities of birds (Avery, 1997), may also promote repellency.

In Experiment 1 we aimed to determine and compare the efficacy of the secondary repellent Avex for deterring free-ranging house sparrows from feeding on wheat,

when used: (a) alone; (b) in combination with cinnamon oil (containing olfactory and, perhaps, taste cues); (c) in combination with a novel visual cue (blue colour); or (d) in combination with d-pulegone (a reported primary repellent containing olfactory and taste cues; Mason, 1990; Wager-Page and Mason,1996). We chose these combinations of repellent cues based on previous research that had identified their efficacy individually (e.g. d-pulegone; Mason, 1990), as well as their potential to be incorporated into pesticide baits to protect non-target birds from poisoning (e.g. cinnamon oil; Spurr, 2000). We hypothesized that the repellent effect of Avex would be enhanced by any novel odour, visual or taste cue. In Experiment 2, we aimed to compare the efficacy of: (a) green colour used alone; (b) blue colour used alone; and (c) the combination of blue colour and the secondary repellent Avex, for deterring sparrows from feeding on wheat. In this experiment, we hypothesized that sparrows would initially be deterred from feeding on coloured wheat but the effect would fade over time, and that long lasting repellency could be promoted by combining a primary cue, such as colour, with a secondary repellent. Others have found that some species at risk of poisoning with pesticide baits, such as robins (*Petroica australis*; Hartley *et al*, 1999), are only deterred by novel coloured foods for short time periods.

Methods

The following experimental protocols were approved by an independent Animal Ethics Committee (Ruakura AEC approval 3136).

Study populations

Sparrow populations at eight sites in and around Havelock North, Hawke's Bay, New Zealand were used in Experiments 1 and 2 during the breeding season (October to December 2000). The sites had been used one year earlier to assess the effect of repellents on sparrow feeding behaviour (August to November 1999; Chapter 2) and were located in urban or semi-rural privately owned properties. Each population had nesting and roosting sites within 100m of a feed table.

Apparatus

The feed table (Chapter 1, Figure 1) was composed of a $1m^2$ metal platform raised on four legs 1.2m above the ground, on which four food trays were placed. These 25cm round plastic food trays were arranged in a square, 20-30 cm apart in the corners of the table. Each table had a roof that extended over the entire table 50cm above the food trays to protect the food from rain. Sparrows were trained to eat plain hulled wheat from the trays. The training procedure involved placing 50g of fresh wheat in each of the four food trays each day and leaving it there until sparrows discovered and began eating the wheat. Any wheat that had not been eaten each day was removed and replaced with fresh wheat. The sparrows in each of these populations had been trained to feed on wheat previously (Chapter 2) and rapidly began consuming all of the wheat offered each day. All tables were supplied with wheat for more than three weeks prior to starting the experiments.

The sparrow populations were 1.5-5km apart. As sparrows are routinely sedentary during the breeding season (Heather and Robertson, 1996), we considered each population to be independent of the others. We did not identify any individual sparrows in the populations, but previously there were more than 20 sparrows at all sites (Chapter 2). Observations suggested that the only other bird species that chose occasionally to feed from the tables were the blackbird (*Turdus merula*) and the greenfinch (*Carduelis chloris chloris*), but these feeding events were very rare.

Experiment 1

In this experiment, we measured the quantity of food remaining for the sparrow populations when offered wheat treated with 2% Avex in combination with either a visual or a combined olfactory/taste repellent.

Treatments   Six wheat formulations were used: (1) plain wheat; (2) wheat with Avex – a commercially available repellent containing 50% 9,10-anthraquinone (CAS No. 84-65-1; Loveland Industries Inc., USA) at a 2% concentration; (3) wheat with Avex at a 2% concentration + cinnamon oil (Bush Boake Allen, Auckland, New Zealand) at a 0.01% concentration; (4) wheat with Avex at 2% concentration + blue colour (Royal blue permanent colour powder H6406, International Flavours and Fragrances, Auckland, New Zealand); (5) wheat with Avex at a 2% concentration +

d-pulegone (CAS No. 89-82-7; Aldrich Chemical Company Inc., USA) at a 0.5%
concentration; and (6) wheat with Avex at a 2% concentration + d-pulegone at a 2%
concentration.

Each repellent combination was mixed into a solution of warm water (~35 C^O) and
applied to the surface of the wheat at a rate of 10% of total wheat weight. The
repellent solutions were poured into plastic containers containing plain wheat and
were vigorously mixed through the wheat by shaking the containers for one minute.
Each treatment was then laid on flat plastic trays to dry (the temperature range in the
room was 18 to 28 C^O), away from direct sunlight. After being air-dried (for up to
3hr) the treatments were sealed in airtight containers until used. The wheat
treatments were prepared less than 72hr before first being offered to the sparrows.
Plain wheat was also soaked in water and re-dried in the same manner as the
repellent wheat treatments.

Test procedure   During the treatment period, sparrows were offered a daily
choice between one tray of 50g plain wheat, one tray of 50g Avex-treated wheat, and
another two trays containing two of the remaining four wheat treatments. The
treatments were presented using a 6 x 6 Latin square design for the six pairings
possible of the four repellents. The last two columns of the Latin square were
deleted and a row allocated to each of six of the eight populations. The remaining
two populations were each allocated four of the pairings, so that each received the
four repellents twice, none of the pairings more than once, and between them, four
pairings once and two pairings twice. Using a changeover design for four periods,
each repellent was offered to each sparrow population for a four-day period, with a
three-day break between every period. The position of each type of wheat was
rotated on the tables daily so that birds did not associate a single position on the feed
table with a particular wheat treatment.

Pre-measured quantities of the treated and plain wheat were introduced to each
population between 0700 h and 0900 h daily. At the end of each 24hr period all
wheat was removed from the individual trays and any remaining wheat was
weighed. A fresh batch of wheat treatments were then placed in the four feed trays
for the next 24hr period. We did not measure the mass of wheat spilled by sparrows
in this experiment because it would not have been possible to distinguish which

wheat treatment the spillage had come from, as most of the treatments did not differ visually. Visual inspections of the tables, and video recordings of sparrows feeding on the tables, indicated that wheat spillage would have accounted for only a small quantity of total wheat removed (on one occasion we measured spillage and found that only 4g wheat was spilled on the surface of the table, from 200g offered).

Experiment 2

In this experiment we compared the efficacy of 2% Avex paired with a blue colour cue, to that of green or blue colour alone for deterring sparrows from feeding on wheat. We used the same sparrow populations described in Experiment 1, with a 35-day interval between experiments.

Treatments   The wheat was treated with repellent in the same manner as for Experiment 1. Four treatments were presented: (1) plain wheat; (2) wheat with Avex at a 2% concentration + blue colour (this treatment was identical to the equivalent wheat treatment used in Experiment 1); (3) wheat with green colour only (0.01% Special Green V200A dye; Bayer NZ Ltd, Auckland, NZ); and (4) wheat with blue colour only (same dye as used in Experiment 1). The treatments were mixed with water and applied to the surface of the wheat at a rate of 10% of total wheat weight as described for the previous experiment. The wheat treatments were prepared less than 72hr before being offered to the sparrows and after air-drying (up to 3hr) were sealed in airtight containers until used. The first batch of treated wheat was fed to sparrows for four days (Days 1 to 4 of presentation), after which a second batch of repellent wheat was made and offered on Days 5 to 8 of presentation. Freshly treated wheat was used for Days 5 to 8 as we did not know if the treated wheat would remain repellent for any longer than four days (the period over which the wheat remained repellent in Experiment 1).

Test procedure   During the eight-day treatment period, sparrows were offered a daily choice between one tray of 50g of plain wheat and one tray of 50g of each of the three repellent-treated wheat types. The positions of each wheat treatment were rotated around the trays each day so that birds did not associate one position on the feed table with any one treatment. Pre-measured quantities of each

wheat treatment were introduced to each population between 0700 h and 0930 h each day. The wheat remaining in each tray after 24hr was removed and weighed and a fresh batch of the wheat treatments was placed in the feed trays for the next 24hr period.

Data analysis

All statistical analyses were conducted using procedures in the Genstat 6.1 statistical package (Lawes Agricultural Trust, Rothamsted Experimental Station, Hertfordshire, United Kingdom). In Experiment 1, percentage intakes of each wheat treatment eaten every 24hr were analysed using the REML procedure. Statistical models included population, period and population by period as random block effects, with a fixed treatment term for repellent. It was also possible to separately assess population by treatment and population by period as random sources of variation. This rejected the population by period interaction as a significant error term (p>0.05), so the Wald statistic for repellent effects was tested as an F-ratio using the population by period degrees of freedom. In Experiment 2, the percentage intake data were analyzed using analysis of variance, with population as a random block term.

In both experiments the four-day periods or eight-day block were treated as repeated measures data and investigated in two steps: (1) an overall split-plot in time analysis was used to indicate possible time trends; and (2) relevant orthogonal polynomial contrasts among the days, plus within day averages, and each of the separate days, were analyzed. In both experiments, intake of plain wheat reached 100% for nearly all populations every day, resulting in severe heteroskedasticity so these data were excluded from all statistical analyses. Use of the angular transformation (arcsin[sqrt[proportion]]) resulted in only minor changes to statistical tests, so these transformations were not used.

Results

Experiment 1

Sparrows consumed over 90% of plain wheat offered on the first two days of presentation, rising to 100% of plain wheat at all tables on Days 3 and 4 (Figure 1).

We detected significant sparrow population ($P = 0.011$) and time period ($P = 0.002$) variation in the overall level of consumption of repellent-treated wheat, although there were no population by repellent type or time period by repellent type interactions ($P > 0.10$). The type of repellent treatment significantly affected wheat consumption on all days of presentation ($P < 0.001$), with all repellent treatments being eaten less readily than plain wheat (Figure 1).

Figure 1:   *Mean (± SED) daily percentage of wheat eaten over the four-day test periods in Experiment 1 by house sparrows offered a choice between plain wheat, 2% Avex-treated wheat and two of the other wheat treatments: 2% Avex + cinnamon oil (novel odour), 2% Avex + 0.5% d-pulegone, 2% Avex + 2% d-pulegone or 2% Avex + blue dye (novel colour).*

The four-day average consumption of plain wheat and each type of repellent-treated wheat is summarized in Table 1. Consumption of Avex only-treated wheat was not significantly different to that of Avex + cinnamon oil ($P > 0.10$). Both of these treatments were eaten more readily than Avex + 2% d-pulegone ($P < 0.01$) or Avex + blue-treated wheat ($P < 0.01$). Avex only-treated wheat was also eaten more readily than Avex + *0.5%* d-pulegone-treated wheat ($P < 0.05$), and Avex + 0.5% d-pulegone was eaten more readily than the Avex + blue treatment ($P < 0.05$). The mean consumption of Avex + 2% d-pulegone-treated wheat was not significantly different to the mean consumption of Avex + blue-treated wheat ($P > 0.50$). We did not detect any significant linear ($P = 0.520$), quadratic ($P = 0.122$) or cubic ($P = 0.244$) changes in the pattern of wheat consumption for any of the wheat treatments over the four-day test period (Figure 1).

Table 1: *Mean four-day consumption (% of offered wheat ± SE) of each type of repellent-treated wheat and plain wheat, showing ranking of repellents from most to least consumed. Significantly different means are indicated by different superscript letters.*

Wheat treatment	Mean consumption (%± SE)	Ranking
Plain	97.2 ± 3.5^{A}	Not repellent
Avex alone	54.3 ± 4.4^{B}	Least repellent
Avex + cinnamon oil	40.9 ± 6.0^{B}	
Avex + 0.5% d-pulegone	25.2 ± 5.3^{C}	
Avex + 2% d-pulegone	$14.6 \pm 3.3^{C, D}$	
Avex + blue colour	9.6 ± 2.2^{D}	Most repellent

Experiment 2

Sparrows readily ate over 95% of plain wheat on Days 1 and 2 of presentation and 100% of plain wheat at all tables on Days 3 to 8 of presentation (Figure 2). Over all days, there was a significant effect of sparrow population on consumption of the different repellent treatments ($P < 0.001$). Throughout the eight-day test period all of the wheat treatments were consumed less readily than plain wheat on every day (Figure 2; $P < 0.001$). On Day 1, all three treated wheat types (green, blue and Avex + blue) were almost completely avoided, with no significant difference between treatments in the percentage of wheat consumed (Figure 2; $P = 0.616$). There was also no significant difference in consumption between treated wheat types on Days 2 ($P = 0.200$) and 3 ($P = 0.115$) of presentation. On Day 4 ($P = 0.050$) and Day 5 ($P = 0.010$), the percentage of green wheat consumed had increased significantly over that of blue wheat or 2% Avex + blue-treated wheat. Avex + blue-treated wheat was consumed much less readily than green- or blue- wheat on Days 6 to 8 (Figure 2; $P < 0.001$). When averaged over the whole eight-day feeding period, the mean percentage of green wheat consumed (47.5%) was significantly higher than the percentage of blue wheat (35.3%), which was significantly higher than the percentage of Avex + blue wheat consumed (14.7%; SED = 5.7, $P < 0.001$). Significant linear contrasts were observed between wheat treatments over time, with the consumption of green- and blue-treated wheat increasing more rapidly than the consumption of Avex + blue-treated wheat ($P < 0.001$).

Discussion

In Experiment 1, we found that all of the repellents evaluated reduced wheat consumption by sparrows to some degree. Two combinations of primary and secondary repellents were more effective for deterring sparrows from feeding than the secondary repellent used alone. The combinations that utilized novel visual cues (blue colour + Avex) or aversive olfactory/taste cues (d-pulegone + Avex) were more effective than Avex alone. The combination that used olfactory/taste cues with limited repellency (cinnamon oil + Avex) was no more deterrent than Avex alone. In Experiment 2, we demonstrated that visual cues alone did not provide the long-lasting repellency offered by the combination of blue colour + Avex.
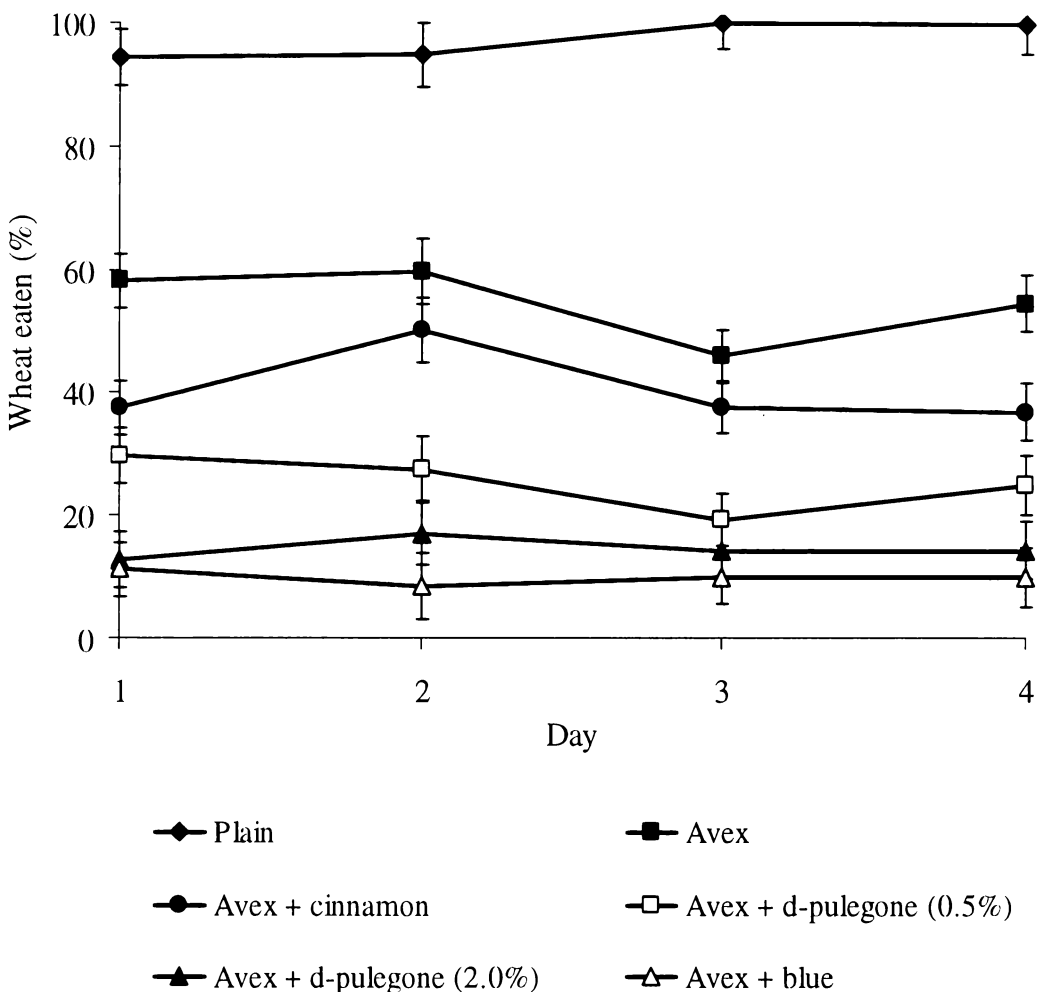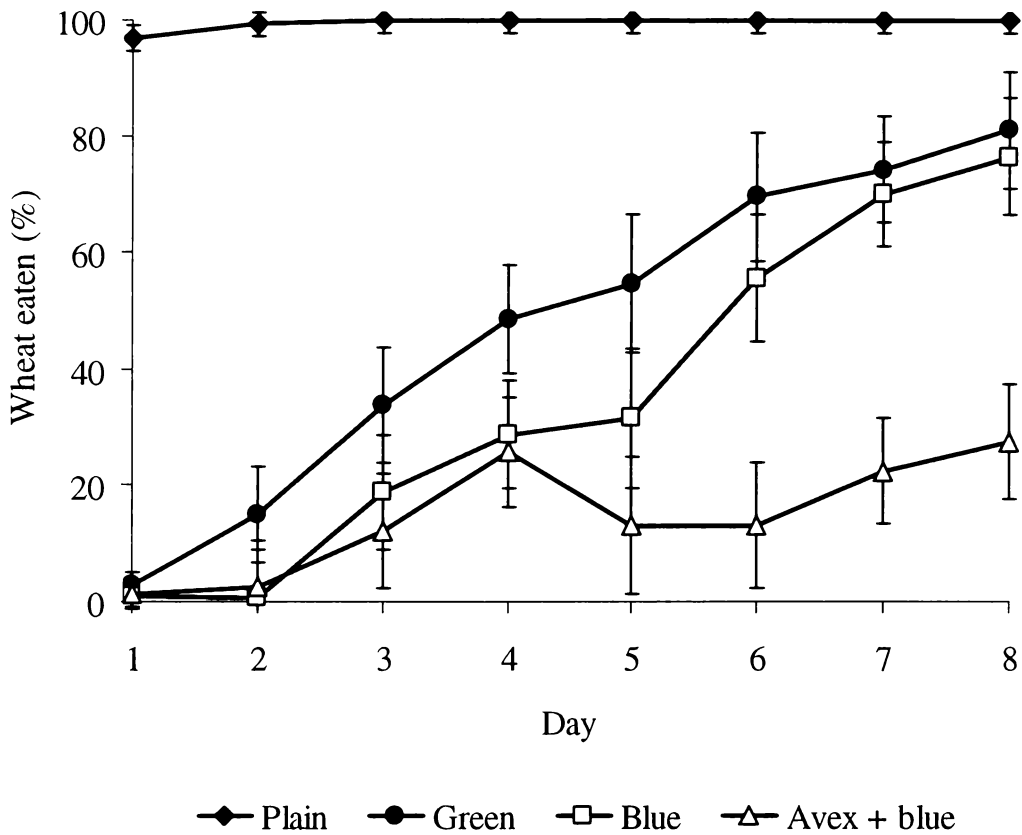
Figure 2:   *Mean (± SED) daily percentage of wheat eaten over the eight-day test period in Experiment 2 by house sparrows offered a choice between plain wheat and three types of treated wheat: green dye, blue dye or 2% Avex + blue dye in combination.*

Over 50% of the wheat treated with Avex alone (Experiment 1) was consumed by sparrows each day, with no evidence for any changes in the pattern in consumption across days. Most other studies have also found that anthraquinone does not completely eliminate feeding (Avery *et al*, 1997; Avery *et al*, 1998; Chapter 2), but these studies have usually observed a learning associated decrease in treated food consumption over time (Avery *et al*, 1997; Chapter 2; Dolbeer *et al*, 1998). We did not observe these temporal effects here. It is possible that the daily composition of the sparrow populations varied in our study, with new sparrows sampling the treated

wheat for the first time on each of the test days, thereby increasing the daily consumption of treated food and disguising any temporal patterns in wheat consumption. For example, Avex treatment may have been very effective on individual sparrows that had learned an aversion, but if new individuals arrived and sampled wheat each day, the overall wheat consumption pattern for the population may not have changed. The level of wheat consumption varied from table to table and from day to day, and this was probably because of differences in sparrow population size, the degree to which they were trained to feed on the tables, changes in weather, or availability of other food sources that we could not account for in this study. Population turnover and day-to-day changes in flock composition were suggested to reduce the effectiveness of another anthraquinone-based repellent formulation, Flight Control, for preventing red-winged blackbirds (*Agelaius phoeniceus*) from feeding on wild rice (Avery *et al*, 2000). While our data does not determine whether individual sparrows would be deterred by Avex from eating lethal quantities of pesticide baits, it does indicate that Avex alone may not prevent at least some individuals from eating. Day *et al* (2003) (Chapter 3) found that a proportion of North Island robins (*Petroica australis longipes*) were not deterred from feeding on dough baits treated with Avex and d-pulegone.

The repellency of Avex was not enhanced when it was paired with cinnamon oil. Several studies have demonstrated that the addition of a novel odour cue can enhance avoidance learning in birds, but not all odours are equally efficacious (e.g. Roper and Marples, 1997). Insect 'warning odours' can enhance and elicit strong avoidance responses when paired with other novel aspects of a food (Guilford *et al*, 1987; Marples and Roper, 1996; Rowe and Guilford, 1996). In Chapter 2, d-pulegone (containing olfactory and taste cues) enhanced avoidance towards Avex. Repellents that have salient cues associated with them may be most effective (Avery, 1997). Cinnamon oil did not appear to provide these cues for sparrows in this study, and does not readily function as a deterrent for some other avian species (e.g. North Island robin; Day *et al*, 2003). Avex + cinnamon oil-treated wheat had a strong odour (to the human nose) when placed on the food tables, but did not differ visually (to the human eye) from Avex only-treated wheat or plain wheat. We do not know how the taste properties of Avex + cinnamon oil differed from those of Avex alone.

Pairing 2% Avex with a visual cue (blue colour) significantly enhanced its repellency to sparrows. The blue colour + Avex wheat treatment was visually quite distinctive (to humans) from all of the other repellent combinations tested and this may have increased its detectability and memorability to sparrows. Blackwell *et al* (1999) found that Flight Control was more effective when paired with a visual cue. Colours have also been used with other secondary repellents to enhance repellency (Avery and Mason, 1997; Nelms and Avery, 1997). The role of visual cues in enabling many bird species to discriminate between palatable and repellent foods has been demonstrated previously (e.g. Avery and Mason, 1997; Mason and Reidinger, 1983; Nelms and Avery, 1997), so the fact that colour acted as an effective cue in this study is not surprising. The combination of a novel colour + Avex provides promise for deterring avian species from eating pesticides and should be investigated further.

Blue colour deters several avian species from feeding, including sparrows (Gionfriddo and Best, 1996; Greig-Smith and Rowney, 1987; Pawlina and Proulx, 1996). In Experiment 2, we found that colour alone (either blue or green) did not elicit long-lasting avoidance responses, even though it was almost completely avoided initially. Other birds, such as robins (Hartley *et al*, 1999) and weka (*Gallirallus australis*; Hartley *et al*, 2000) also readily habituate to foods associated with lowly preferred colours (like blue), unless they possess other repellent characteristics. Novelty is an important factor in food avoidance responses, especially at first exposure (Avery, 1997), so we may have expected the sparrows to avoid the green wheat (which had never been offered before) more strongly than the blue wheat. We found no evidence that birds habituated to the blue coloured wheat (which had been offered in combination with Avex in Experiment 1) more readily than the green wheat. In fact, a greater percentage of green wheat was eaten over the whole eight-day period than blue wheat. However, avoidance of blue wheat in Experiment 2 may have been a result of some sparrows generalizing their learned avoidance of the blue + Avex-treated wheat (from Experiment 1 or learned during Experiment 2) to all blue wheat, including wheat without Avex in it. Alternatively, our data may indicate a less strong avoidance of green food over blue food.

Pairing Avex with d-pulegone also significantly increased repellent effect, compared to Avex alone, at both of the concentrations of d-pulegone tested. In

Chapter 3 we previously demonstrated the high efficacy of this repellent combination, suggesting that d-pulegone provided additional salient cues (odor and taste) or repellency (or both) that appeared to be lacking when Avex was presented alone. D-pulegone repels birds via taste and olfactory cues (Mason, 1990). Some studies have found that d-pulegone requires minimal or no consumption to cause total avoidance (Wager-Page and Mason, 1996), while others have found that d-pulegone-treated food reduces, but does not eliminate, consumption by sparrows (Chapter 2). We did not determine the relative roles of the taste and odour cues present in d-pulegone for enhancing repellency, but d-pulegone provided significantly better repellency enhancement than cinnamon oil, the other odour tested (which may also have had taste cues). The combination of 0.5% or 2% d-pulegone + 2% Avex is well suited to protecting non-target birds from poisoning and 2% d-pulegone + 2% Avex has been used successfully to deter robins from sampling non-toxic pesticide baits (Chapter 3).

  Combinations of a secondary repellent with certain additional visual or olfactory/taste cues proved to be highly effective for deterring sparrows from feeding. While not all cues were equally effective (e.g. cinnamon oil did not enhance repellency), our data provide further evidence for the role that multiple cues play in enabling birds to make safer feeding choices. We chose our repellent combinations for this study based on previous research and our assumptions about the sensory abilities of avian species. While this approach can be successful, better understanding of the perceptual capabilities and sensory systems of the target animals may lead to even more effective repellent design (Avery, 1997). In this study, we did not quantify the mechanisms by which our repellent combinations worked, or the relative contributions that each component provided. Further research to understand these mechanisms and perceptual abilities may lead to more efficient and cost-effective designer repellents.

Management implications

The current study has identified several promising combinations of repellents and cues for deterring birds from damaging valuable crops and for reducing the likelihood of them consuming pesticide baits or other harmful substances.

Combinations of blue colour + 2% Avex or 2% d-pulegone + 2% Avex proved to be equally effective for deterring sparrows from feeding, although the longevity of repellent effects for each combination have yet to be determined. From a practical viewpoint, it may be most cost effective to incorporate colour + Avex combinations into baits, as many baits are already dyed colours that are thought to be lowly preferred by non-target birds (e.g. Hartley *et al*, 2000). Food dyes would be less expensive to incorporate into baits than odour/taste cues, such as d-pulegone.

Further research is required with a range of avian species to determine the efficacy and cost-effectiveness of these combinations in the field. Phytotoxic or other effects will need to be determined for crop- or turf-based applications, and using colour treatment may not be suitable in some circumstances (e.g. on turf around parks or golf courses). For use on pesticide baits, phytotoxic effects are unimportant. If pesticide baits were already coloured, and thereby had a distinctive visual cue, it may be possible to incorporate Avex with an additional olfactory or taste cue to provide maximal protection. However, when using repellent cues on pesticide baits it is critical that the combination of repellents does not compromise the efficacy of target pest control (Spurr *et al*, 2001). Day *et al* (2000) have demonstrated that combinations of d-pulegone + Avex and blue colour + Avex are both accepted by some target pest species, such as brushtail possums (*Trichosurus vulpecula*) and rats (*Rattus* spp.). Additionally, repellent combinations will need to be effective for the wide range of avian species that encounter pesticide baits.

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Summary:

In this chapter (Chapter 4), I found that several combinations of repellents were effective for reducing food consumption by sparrows. Combinations of Avex with additional visual or olfactory/taste cues modified the feeding behaviour of sparrows. 2% Avex + 2% d-pulegone and 2% Avex + blue colour elicited the most effective avoidance responses. I hypothesised that these combinations provided strong visual or olfactory/taste cues that enabled sparrows to form robust learned avoidance responses. Colour alone (in the absence of Avex) was not an effective repellent, with sparrows habituating and beginning to eat the coloured wheat over time.

In the context of deterring birds from eating mammalian pest control baits, it may be more cost effective to incorporate a colour + Avex repellent combination into baits than d-pulegone + Avex, as many baits are already dyed colours that are lowly preferred by non-target birds. Therefore, in the next chapter (Chapter 5), I tested the efficacy of blue colour + 2% Avex for deterring robins from feeding on baits. I compared the feeding responses of robins towards standard and repellent-treated baits in choice and no-choice tests, to mimic the situation in which robins may find baits in the wild. I also tested the efficacy of the blue colour + Avex repellent combination in different seasons and amongst different age and gender classes of robins to determine if some robins in a population may be more vulnerable to poisoning than others or at particular times.

Chapter 5

Feeding behaviour of New Zealand's North Island robin *Petroica australis longipes* is modified by combining a novel colour with a secondary repellent

Tim D. Day, Kylie E. Flight, Lindsay R. Matthews and Joseph R. Waas

Abstract

Repellents may reduce the risk of death for non-target birds during poison-based control operations aimed at mammalian pests. We investigated whether the addition of a novel visual cue and a secondary repellent (Avex, an anthraquinone-based product) to baits influenced the feeding behaviour of wild North Island robins (*Petroica australis longipes*). Robins were trained to approach observers within their territory and were offered repellent-treated (blue colour + 2% Avex) and standard (green colour + cinnamon oil, as used for pest control operations in New Zealand) dough baits over four consecutive days on a test arena on the forest floor. We used choice and no-choice tests to record the feeding behaviour of robins towards the baits in the austral winter and summer. Robins pecked at standard baits more frequently than repellent baits, with the frequency of pecking at repellent bait declining over the four days. They pecked more frequently at both bait types in the winter than summer, and juvenile robins tended to peck at repellent bait more frequently than adult males or females. Choice and no-choice tests produced similar levels of pecking response towards both bait types. On occasions, the baits were removed from the arena: standard baits removed were consumed readily but, with the exception of one juvenile bird, repellent baits were not. The results demonstrated that, relative to standard baits, the combination of blue colour + 2% Avex effectively deterred most robins from feeding, with evidence of learned avoidance. However, we found that robins are likely to sample all baits more readily in the winter than summer and some juvenile robins may not be deterred by the repellent combination. Since blue colour + 2%

Avex was effective in deterring feeding on a highly preferred base material, it is likely, for most robins, to reduce their propensity to be poisoned during pest control operations.

Keywords: anthraquinone; bird repellent; colour; feeding behaviour; North Island robin; pest control.

Introduction

Poisonous baits and pesticides are used around the world to kill a wide range of mammalian and invertebrate pests, but non-target birds sometimes die when they consume the treated bait. A significant body of research has focused on identifying cues or repellents that could be used to modify the feeding behaviour of birds, without compromising bait acceptance by the target pests (e.g. Spurr *et al*, 2001). Repellents have either primary or secondary modes of action (Rogers, 1978). Primary repellency requires little or no learning, as birds instantaneously avoid cues associated with the treated food (Clark, 1998). Secondary repellency results from an illness-induced learned avoidance of the treated food, but requires ingestion of some treated food before learning can occur (Clark, 1998). Primary repellents pose a risk of poisoning to any bird that habituates to the effects of the primary repellent (Domjan, 1998) and begins to eat bait, whereas secondary repellent will not prevent poisoning if avoidance learning does not occur before a bird has consumed a lethal quantity of the pesticide.

  Combinations of repellent stimuli with primary and secondary modes of action may be more effective at deterring birds than single repellents. Addition of a novel visual cue (Chapter 4; Greig-Smith and Rowney, 1987) or a novel odour cue (Chapter 2; Chapter 4; Roper and Marples, 1997) enhances avoidance learning towards secondary repellents. Avian colour vision is highly developed and in most species is the primary cue used for making feeding decisions (Avery, 1997). Not all odours are as effective for enhancing avoidance learning as visual cues (Mason and Reidinger, 1983) or tastes (Beauchamp, 1997). However, methyl pyrazine (an insect warning odour) enhances and elicits strong avoidance responses (Guilford *et al*, 1987; Marples and Roper, 1996; Rowe and Guilford, 1996). By combining appropriate repellents with

salient olfactory, visual or taste cues, enhanced repellency may be achieved (Avery and Mason, 1997; Nelms and Avery, 1997; Sayre and Clark, 2001).

In New Zealand, the widespread use of toxic baits for vertebrate pest control has caused some mortality of non-target native birds (Spurr, 2000), so bait manipulations to modify the feeding behaviour of birds have been employed. The New Zealand Pesticides Act (established in 1979) requires that all baits must be larger than 16mm, so birds cannot readily manipulate them, and all baits must be dyed green, a colour believed to be unattractive to birds (Caithness and Williams, 1971). Additionally, cinnamon oil is frequently added to bait as an avian deterrent. Unfortunately, native birds still die during pest control operations that use large green-dyed, cinnamon-flavoured baits (Spurr, 2000). We found that green- and cinnamon oil-treated baits did not deter robins from feeding (Chapter 3) and cinnamon did not enhance the repellent effects of Avex for sparrows (Chapter 4).

New Zealand's North Island robin (*Petroica australis longipes*) is particularly vulnerable to poisoning (Powlesland *et al*, 1999) and has previously been observed eating toxic cereal and carrot baits (Spurr and Powlesland, 1997). Robins are small (18cm, 35g) territorial forest passerines. Their diet consists mainly of invertebrates, supplemented by small fruits in summer and autumn (Heather and Robertson, 1996). They feed predominantly on the forest floor by gleaning invertebrates from the leaf litter and rely largely on sight to find their prey (Powlesland, 1981b). Seasonal differences in prey availability, however, cause robins to feed on the ground more frequently in winter than summer, and feed on arboreal invertebrates when they are available during the summer months (Powlesland, 1981b). Male robins engage in courtship feeding with females prior to nest building and continue to feed their mate throughout incubation (Heather and Robertson, 1996). Juvenile robins are fed by one or both parents for between four and seven weeks after fledging (Armstrong *et al*, 2000; Powlesland *et al*, 2000), but begin foraging for themselves from two weeks, spending more time feeding on the ground than adult birds (Powlesland, 1981b). Once fledged, they usually disperse from their natal territory within 10 weeks. Seasonal, gender and age class differences in robins' feeding behaviour may affect the vulnerability of different robins to poisoning at certain times of the year. Wild robins are an ideal species for evaluating repellents in the context of pest control in New Zealand, as they respond positively towards humans and will approach to take food (Maloney and McLean, 1995).

Previous research with robins has identified strong colour preferences, with birds preferring red and yellow coloured food over green or blue food (Hartley *et al*, 1999). Furthermore, blue coloured food is less attractive to robins than green (Hartley *et al*, 1999), and is accepted by pests (Day and Matthews, 1999), so offers potential as a cue to deter robins from baits. However, in many species, including robins, lowly preferred bait colours alone do not provide a long-lasting deterrent effect (e.g. Chapter 4; Hartley *et al*, 1999), so must be combined with other cues to be effective. Day *et al* (2003) (Chapter 3) found, in choice tests, that wild robins were deterred from feeding on baits treated with the combination of a primary repellent (2% d-pulegone) and secondary repellent (2% Avex, an anthraquinone-based product). D-pulegone acts via strong olfactory and taste cues (Mason, 1990), and may have acted as a salient cue for a learned aversion caused by the anthraquinone (Day *et al*, 2003). Birds taste anthraquinone-treated food, experience the post-ingestional effects, and thereby learn to avoid the treated food (Avery *et al*, 1997). However, this particular combination of repellents may not be effective for use in pest control baits, as the highly volatile olfactory cues present in d-pulegone may not persist in the field. An alternative, more cost-effective combination, using a novel colour (blue) + 2% Avex, was equally efficacious as the 2% d-pulegone + 2% Avex combination for deterring house sparrows (*Passer domesticus*) from feeding (Chapter 4). This repellent combination was also readily accepted by the target pest species, brushtail possums (*Trichosurus vulpecula*) and ship rats (*Rattus rattus*; Day *et al*, 2000).

In this study, we examined the following questions. First, does the combination of blue colour + 2% Avex effectively deter robins from feeding on baits, in comparison to their feeding responses towards standard baits? We predicted that the repellent combination would reduce the frequency of pecking at baits by robins over repeated exposures and would reduce the rate of repellent bait removal and consumption. Second, do different robin classes (adult males, adult females, or juveniles) behave differently towards baits? We predicted that adult male robins may peck more frequently at repellent-treated baits than females or juvenile robins, as males spend more time foraging, both for themselves and for food for their partner or dependent juveniles. Third, does the feeding behaviour of robins differ in different seasons, or when baits are presented in choice or no-choice tests? We predicted that robins would peck at baits more frequently in the winter than summer, due to higher metabolic

requirements in the colder months. We also predicted that robins may peck at and eat more repellent baits in the no-choice test situation, as many animals are considered to be less sensitive to the effects of repellents in no-choice tests than in choice tests (Clark, 1997). Choice tests provide an excellent opportunity to measure the relative consumption of different baits by individual birds, but no-choice tests, in which the birds are presented only with a single bait type, may better reflect the way in which birds will encounter bait during a pest control operation.

Methods

Subjects

Wild robins ($n = 51$) living on Tiritiri Matangi Island (36°36' S, 174°53'E, Hauraki Gulf, New Zealand) were used, under permit from the New Zealand Department of Conservation. Prior to this study, each bird had been captured and identified with a unique combination of leg bands for population monitoring purposes and the territories of the birds were known (e.g. Armstrong *et al*, 2000). We did not capture or restrict the normal movements of any robins in this study and they had free choice about whether to interact with the observers or baits. The feeding behaviour of some robins ($n = 18$) towards repellent baits had been studied 12 months previously (Day *et al*, 2003; Chapter 3), so we considered these birds to be experienced with repellents and spread them evenly between treatment groups. As part of the population monitoring and earlier repellent study, all birds had previously been trained to approach an observer to receive mealworm larvae (*Tenebrio molitor*). Thirty-four robins (12 adult female, 22 adult male) were used during the austral winter (July 2001), prior to the beginning of the breeding season, and 22 robins (six adult female, nine adult male and seven juveniles for which we could not determine gender) were used in the austral summer, immediately following the conclusion of the 2001/02 breeding season (late February 2002). Five of the birds (three adult males and two adult females) were used in both seasons. All of the juvenile robins were independent of their parents during the experimental period, so were not being fed by their parents; juveniles were regularly chased away by territorial adults (T. Day, *pers.*

observations). The number of male robins used in the study was greater than females because the population was male biased (Armstrong *et al*, 2000), and the strongly territorial nature of male robins means they tended to approach observers more readily than females.

Baits used

We used baked, lard-based dough as our bait, following the recipe of Day *et al* (2003) (Chapter 3). Dough bait was chosen as a carrier for the repellent in this experiment as we had previously demonstrated this to be a highly preferred bait material for robins (Day *et al*, 2003; Chapter 3), and using a preferred bait material gave us a conservative test of repellent effects. The dough was chopped into approximately 5-mm cubes after baking, a size which could be readily manipulated by robins (Hartley *et al*, 1999). Two dough bait types were made: standard bait and repellent bait. The standard bait recipe contained green dye (0.01% wt/wt; Special Green V200A dye, Bayer NZ Ltd, Auckland) and, after being baked and chopped, was surface coated with a solution of water containing 0.1% cinnamon oil (Bush Boake Allen Ltd, Auckland). The cinnamon was added to the baits by "dipping" the chopped dough into the treatment solution in sieves, and then allowing the pieces of dough to air-dry before sealing it in airtight containers. The green-cinnamon standard bait represented the typical bait used currently for pest control in New Zealand. The repellent bait recipe contained blue dye (0.01% wt/wt; Royal blue permanent colour powder H6406, International Flavours and Fragrances, Auckland, New Zealand) and, after being baked and chopped, was surface coated with a solution of water containing 2% Avex (50% wt/wt 9,10-anthraquinone; CAS No. 84-65-1). The solution was added to the baits in the same manner as for standard baits.

Procedure

All procedures described were approved by an independent Animal Ethics Committee (Ruakura AEC approval 3136). We modified the method of Day *et al* (2003) (Chapter 3) to offer the robins the bait materials. A test arena, consisting of a 0.75m x 0.50m area of the forest floor scraped clear of leaf litter, was set up centrally in each robin

territory each day. Robins were attracted to the test arena by the observer tapping with a finger on a plastic container. Once the robins were within 3m, small twigs were tossed into the test arena. This stimulated the robins to alight in the arena and eat invertebrates and investigate the baits. Robins showed a lot of interest in the test arena, as clearing the leaf litter exposed invertebrates that the robins foraged for. We then used the test arena to present robins with the test baits, by placing the baits on the ground.

Robins were offered baits in the test arena for 25 minutes per day (between 0700 h and 1600 h), over four consecutive days. Two teaspoon-sized piles of bait (~20g) were placed side-by-side in the middle of the test arena, with each pile of baits 25cm apart. During the winter period, we offered the baits in either a choice test (robins offered a choice between standard and repellent bait; $n = 20$ birds) or a no-choice test (robins offered two piles of standard bait (n = six birds) or two piles of repellent bait (n = eight different birds)). In the summer, baits were only offered in choice tests ($n = 22$ birds). During choice tests, the position of each bait type on the arena was alternated for each bird each day to remove any position biases.

We used a video camera (Sony TRV310E Digital Handycam) to record the feeding behaviour of each robin during the 25-minute test. The camera was mounted on a tripod 1.5m above the ground and was positioned 2-3m from the arena. In subsequent analyses of the videotapes, every peck directed towards the baits was recorded (using slow-motion playback where necessary). A peck was defined as every contact made by the robins' beak with one of the baits. Two observers were used to analyse the video tapes. To calculate inter-observer reliability, both observers recorded the pecking behaviour of robins from 10 randomly chosen test sessions. The inter-observer reliability for the peck frequency (expressed as the Pearson correlation coefficient) was $r = 0.92$ ($n = 10$, 8 d.f.). If a robin removed one of the baits from the test arena (i.e. picked it up in its bill and flew away with it), the type of bait removed (standard or repellent) and the subsequent fate of the bait (eaten, dropped or taken out of sight) was recorded.

Statistical Analysis

The number of pecks made at the different baits were analysed as Poisson variates using the General Linear Mixed Model (GLMM) in the Genstat 6.1 statistical package (Lawes Agricultural Trust, Rothamsted Experimental Station, Hertfordshire, United Kingdom). Fixed effects for bait type, season, robin class, trial type, and visit number were retained throughout analyses. Terms for location, date, robin by bait and robin by date were retained if statistically significant at the 5% level, but that for robin was retained regardless of statistical significance. The statistical significance for any fixed effect was obtained by calculating an F-ratio from the related Wald statistic, using the minimum of the degrees of freedom from the relevant error strata. There were too few birds in each strata to test third order interactions, such as bait type by season by robin class. Sources of variation considered for the random model comprised bait position on the test arena and whether the robin was naive or experienced in the experimental procedure. Neither of these terms were significant, but they were retained in the model. Means presented were back-transformed and re-scaled from the Poisson model. Standard errors for means reflect the average change resulting from the addition and subtraction of standard errors on the transformed scale. The number of pieces of bait of each type removed (and their subsequent fates) were compared using Chi-square tests.

Results

When robins came onto the arena during the 25-minute test period, they readily explored the cleared litter arena, foraging for invertebrates and investigating the baits. Of the 51 robins tested, only five never pecked at either bait type. Three of these five birds were offered a choice of both bait types in the summer and the other two were offered repellent bait only in winter. Eight further robins (three in the summer choice-test, three in the winter choice-test, and two in the winter no-choice-test offered repellent bait) did not peck at either bait type on Day 1, but began pecking at baits on subsequent days.

  Robins pecked standard baits (mean of 3.9 ± 1.4) more frequently than they pecked repellent baits (mean of 0.8 ± 0.4; $F_{1,121} = 90.22$, $P < 0.0001$) and there was a significant bait type by day interaction ($F_{3,121} = 4.19$, $P = 0.007$). The frequency of

pecking at standard bait remaining constant over exposures, while pecking at repellent bait was lower on Day 1 and declined further over the four days (Figure 1). The total pecking frequency of robins in each test session was greater in the winter (mean of 2.9 ± 0.3 pecks) than summer (mean of 1.3 ± 0.2 pecks; $F_{1,43} = 6.04$, $P = 0.018$), but there was no significant season by bait type interaction (Table 1). Robin class (adult male, adult female, or juvenile) did not affect the overall peck frequency ($F_{2,43} = 0.66$, $P = 0.525$), but there was a significant bait type by robin class interaction (Table 1). The interaction was driven primarily by the highly variable pecking response of juvenile robins towards baits, with a few juveniles pecking more frequently at both bait types than other birds. Choice tests (mean of 3.0 ± 0.4 pecks) and no-choice tests (mean of 2.5 ± 0.5 pecks) produced similar levels of overall pecking response ($F_{1,43} = 1.62$, $P = 0.210$). The interaction between bait type and test type was not significant (Table 1), although, for some robins, the pecking frequency towards repellent baits was higher in no-choice tests than in choice tests. The frequency of pecking at standard baits was very similar in choice and no-choice tests.
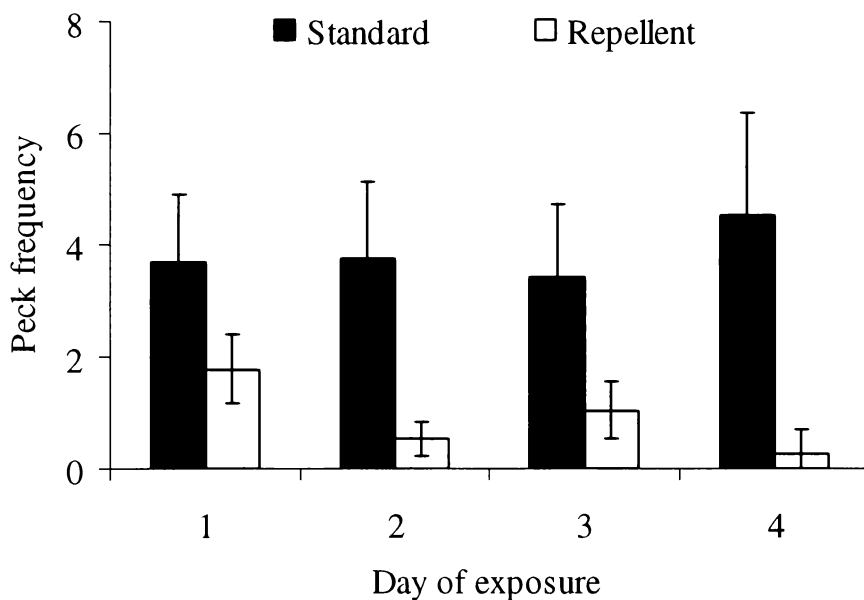
Figure 1:   *Adjusted mean number of pecks (± SE) by robins directed at standard or repellent baits over four days of exposure.*

Table 1:   *Adjusted mean number of pecks (±SE) by robins directed at standard or repellent bait, summarised by season, robin class, and test procedure used. ANOVA's and P values are presented for the interaction between bait type and each factor.*

Factor	Peck frequency (mean ± SE)		ANOVA	P
	Standard	Repellent		
Bait type x season			$F_{1,121} = 0.07$	0.792
Winter	5.5 ± 1.5	1.0 ± 0.4		
Summer	2.5 ± 0.9	0.5 ± 0.2		
Bait type x robin class			$F_{2,121} = 4.05$	0.020
Male	3.3 ± 1.0	0.4 ± 0.2		
Female	3.7 ± 1.7	0.7 ± 0.4		
Juvenile	4.7 ± 3.0	1.6 ± 1.3		
Bait type x test type			$F_{1,43} = 2.81$	0.101
Choice test	3.8 ± 0.9	0.4 ± 0.2		
No-choice test	4.0 ± 2.2	1.3 ± 0.9		

Overall, robins removed standard bait from the test arena more frequently than they removed repellent bait (see Totals, Table 2), with relatively few repellent baits removed. However, repellent bait removal became more common in no-choice tests than choice tests (Table 2; χ^2 (2 d.f.) = 6.1, $P = 0.047$). When we could determine the fate of baits removed, robins ate most standard baits and dropped most repellent baits (Table 3; χ^2 (2 d.f.) = 10.9, $P = 0.004$). Only one instance of repellent bait consumption was recorded, by a juvenile robin during the summer. There were insufficient bait removal observations to test for differences in the behaviour of male, female and juvenile robins when they removed baits. There were no differences in the proportion of standard and repellent baits that were eaten, dropped or taken out of

sight during summer or winter (χ^2 (2 d.f.) = 1.8, P = 0.396), but overall more baits were removed by fewer robins in the winter period (Table 2).

Table 2:   *Total number of standard and repellent baits removed from the test arena by robins during winter and summer choice tests and the winter no-choice test. The fate of the baits removed (eaten, dropped or unknown) is described in Table 3.*

Season and trial type	N (birds)	Standard	Repellent
Summer choice test	22	10	2
Winter choice test	20	26	2
Winter no-choice test	14	18	9
Total	56	54	13

Table 3:   *Total number of standard and repellent baits that were eaten, dropped or taken out of sight (unknown fate) by robins when they removed baits from the test arena.*

Fate of bait	Standard	Repellent
Eaten	10	1
Dropped	3	5
Unknown	41	7
Total	54	13

Discussion

Robins pecked infrequently at repellent baits when first exposed to them and less frequently over subsequent exposures. They rarely removed repellent baits from the test arena, and with the exception of one juvenile robin, appeared to not eat these baits, although the fate of a high proportion of the baits removed is unknown. In

contrast, robins readily pecked at standard bait containing green dye and cinnamon oil throughout the four exposures and ate the majority of standard baits they removed from the arena. Robins have been observed feeding on green-cinnamon flavoured baits previously (Day *et al*, 2003; see Chapter 3; Spurr and Powlesland, 1997) and have been found poisoned after field operations using these baits (Spurr, 2000). Although green dye and cinnamon oil may help to reduce the number of birds that sample baits, green-cinnamon baits should not be considered bird-safe.

The reluctance of robins to peck repellent baits at first exposure may have been a neophobic response towards a novel coloured food, or may have been caused by some innately aversive property of the bait. Neophobia is common towards novel coloured food among avian species (e.g. Chapter 4; Greig-Smith and Rowney, 1987), but does not explain the difference we observed in consumption between the blue repellent baits and the green standard baits, both of which were novel to many of the birds. Hartley *et al* (1999) found that robins preferred green coloured food over blue, and this preference may have been reflected in our results. It is also possible that the combination of blue colour + 2% Avex provided some additional cue to robins (e.g. olfactory or taste) that caused a further reduction in pecking behaviour when baits were first encountered. Ballinger (1999, 2001) suggested that anthraquinone produces ultra-violet visual cues that birds respond to, so if these cues had been present in our repellent baits they may have increased avoidance. Despite being reluctant to peck at repellent baits, several robins may have pecked and consumed sufficient bait to be lethally poisoned had the baits been toxic. One way to minimise the risk of poisoning non-target birds would be to provide repellent-treated non-toxic bait to birds prior to exposing them to the toxic baits. This would allow the birds to safely sample and learn to avoid baits before they were toxic. Pre-feeding pest populations with non-toxic bait prior to toxic baiting is recommended in New Zealand to maximise pest kills (e.g. Moss *et al*, 1998), and repellents could readily be incorporated into the non-toxic pre-feed.

The frequency of pecking at repellent baits declined over exposures, suggesting that robins developed a learned avoidance response after initially sampling the bait. We did not, however, conduct further experiments to prove the formation of learned avoidance responses in the robins. The active ingredient in Avex, anthraquinone, is a recognised secondary bird repellent (Avery *et al*, 1997), and Avex alone may have

caused robins to, at least partially, avoid baits if it had been tested. However, the blue colour used here may have reduced initial bait sampling (as for sparrows in Chapter 4) and acted as a salient visual cue for development of the aversion. We found that learned avoidance of Avex-treated bait is enhanced in house sparrows by the addition of novel visual or olfactory/taste cues (Chapter 4). An alternative pairing of d-pulegone (containing olfactory and taste cues) + Avex, also caused a similar reduction in pecking behaviour by robins (Day *et al*, 2003; see Chapter 3), but would be more expensive to apply to baits.

Juvenile robins showed variable responses to bait, with some birds almost completely avoiding baits and others pecking frequently at both bait types. While the mean pecking frequency of juveniles did not differ to that of adult males or females, there was a significant bait type interaction, caused by some juveniles being undeterred from pecking the repellent baits. Two juvenile birds pecked at repellent baits more than 10 times within a test period, with one of these robins eating a piece of repellent bait it removed from the test arena. Based on the average size of dough bait fragments pecked by robins (~0.04g, Day *et al*, 2003; Chapter 3), it is possible that these birds would have been lethally poisoned had the baits been toxic. No other birds were observed to eat repellent bait. Juvenile robins feed primarily from the ground, being less proficient than adults at finding arboreal invertebrates (Powlesland, 1981b), so it is possible that juvenile birds were more prepared to sample the aversive baits, as they represented an 'easy' meal. Survival of juvenile robins on Tiritiri Matangi is density dependent and the island was at carrying capacity during this experiment (Armstrong and Ewen, 2002). This meant that many juvenile robins did not hold territories, were chased when in adults' territories (Armstrong *et al*, 2000) and, therefore, did not have exclusive food supplies when we offered baits. Additionally, juvenile animals of some species are less cautious in their feeding behaviour than adults, having to learn about safe and unsafe foods and situations. Powlesland *et al* (2000) found that juvenile robins often accept mealworms from humans immediately, whereas many adult birds will not initially take the mealworms offered. The juvenile robins used in this study had been independent for only one to two months, so had relatively little experience in selecting safe foods. Additionally, these juveniles had been previously trained to receive mealworms from observers, so were familiar with receiving food rewards

when humans were present: this may have increased their propensity to eat baits. Nevertheless, our results suggest that some juvenile robins may be at risk of poisoning when offered repellent baits, so ideally control operations should be delayed if recently independent juveniles are present in a population.

We did not detect any difference in the feeding behaviour of male and female robins. Day *et al* (2003) (Chapter 3) previously found that male robins were more prepared to peck at d-pulegone + Avex-treated baits than females during the winter. Male robins routinely feed their mates and juveniles in the breeding and fledging periods (Armstrong *et al*, 2000) and it is possible that males are more prepared to thoroughly test a range of potential food sources than females in some circumstances. The blue colour + Avex combination we used in the current experiment may have been more effective than d-pulegone + Avex for deterring male robins from feeding. Alternatively, males tested here may have had more alternative food sources, or better climatic conditions, than males tested in the previous winter, and therefore may have been under less pressure to sample repellent baits.

Overall, robins pecked at baits and removed them from the test arena more frequently during the winter than the summer. The robins' primary priority is to find enough food to meet metabolic requirements, with more food needed and more time spent foraging during the colder winter period (Powlesland, 1981a). The higher pecking frequency we observed in the winter may have been a function of an overall increase in feeding behaviour by robins at this time of year. If however, we had conducted our experiments earlier in the summer, when adult robins were feeding dependent juveniles, we may not have seen this difference in pecking behaviour. Robins tend to spend more time feeding on the ground in the winter because the leaf litter and soil are moist, providing ready access to large invertebrates, such as earthworms (Powlesland, 1981b). In contrast, during the summer months, more arboreal and flying invertebrates are available and adult robins prey heavily on these species. Also, the ground is usually harder during the summer, limiting robins' access to ground dwelling invertebrates (Powlesland, 1981b). It is possible that robins in this study spent less time foraging on the test arena during our summer tests, and therefore pecked less frequently at baits, but we did not measure this variable. Differences between the seasons in the availability or attractiveness of alternative prey may also have accounted for the overall lower pecking response

during the summer. When few ground invertebrates are available in the summer, robins may supplement their diet with small fruits (Heather and Robertson, 1996). In our study, robins did not peck at baits more frequently in the summer than winter, so did not appear to 'take advantage' of the dough baits as a significant supplementary summer food source. No interaction was observed between season and bait type, suggesting that the repellent baits remained unattractive, even when alternative foods sources may have been limited.

The total pecking rate of robins, and the rate at which they pecked at standard baits, did not differ between choice and no-choice tests, with robins eliciting only a certain number of pecking responses during each test period. Twice as much of the standard bait was available to robins in the no-choice tests, but they did not peck more frequently at the extra bait. We suggest that robins were usually sated well before the end of each choice-test period, so did not peck more frequently at standard baits even when more was available in the no-choice situation. As robins do not have a crop, they do not continue to eat once their immediate metabolic requirements have been met, even when additional palatable food is present (Powlesland, 1981a). While the mean values for pecking at repellent baits were not significantly different between choice and no-choice tests, some robins offered repellent baits in no-choice tests appeared to peck at them more readily than birds offered repellent baits in choice tests. Robins also removed repellent baits from the test arena more frequently during the no-choice tests, but except for one bird, did not eat them. Animals are considered to be less sensitive to the effects of repellents in no-choice tests than in choice tests (Clark, 1997) and repellents that are effective in the choice situation may not work in no-choice tests or in the field. Our data suggest that, some robins at least, were more prepared to sample or remove baits in no-choice tests, but this behaviour apparently did not result in bait ingestion. The no-choice test we used mimics the conditions in which robins would find baits during a control operation (i.e. a single type of bait on the forest floor), and therefore, the blue colour + Avex repellent we tested here is likely to afford protection to many wild robins.

The results of the current research suggest that the combination of a novel visual cue and a secondary repellent will effectively deter feeding on baits by most robins. There is significant potential for this or additional combinations of repellent cues to be used to protect a range of bird species from pesticide baits. We did not test any

individual repellents with robins, so it is also possible that Avex alone may have been an effective deterrent. However, any single repellents or combinations of cues must be acceptable to target pests. The most cost-effective way to incorporate effective combinations of repellents into baits should be determined. For example, identifying the minimum concentration of secondary repellent required to cause avoidance will minimise the cost of applying repellents to bait, and may also ensure that target pests are not deterred. Critical to the success of a repellent, will be its ability to deter other bird species that are likely to feed on baits. For example, North Island tomtits (*Petroica macrocephala*) are as vulnerable to poisoning as robins, and have similar feeding behaviour (Heather and Robertson, 1996), but we do not know if they will be deterred by the repellents. Finally, the ability of repellents to protect birds during actual pest control operations, and the efficacy of the repellent baits for controlling target pests, needs to be confirmed under the varied conditions encountered during normal pest control operations.

Acknowledgements

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Summary:

In this chapter (Chapter 5), I recorded the feeding behaviour of robins towards standard and blue colour + 2% Avex repellent-treated pest control baits, using choice and no-choice tests in different seasons. I found that, relative to standard baits, the combination of blue colour + 2% Avex effectively deterred most robins from feeding, with evidence of learned avoidance. However, I also found that robins are likely to sample all baits more readily in the winter than summer and some juvenile robins may not be deterred by the repellent combination. The blue colour + 2% Avex combination shows promise for deterring native birds from being poisoned during pest control operations.

  In the last experimental chapter of the thesis (Chapter 6), I determined whether the same repellent combination also deterred a similar species, the tomtit from feeding on baits. I chose to test the repellent with tomtits because, although they are closely related to robins, they appear to be more vulnerable to poisoning than robins in some circumstances. Therefore, I was interested to understand whether tomtits were more prepared to sample baits containing repellent than robins.

Chapter 6

Feeding responses of North Island robins and North Island tomtits to pest control baits treated with bird repellents

Tim D. Day, Joseph R. Waas and Lindsay R. Matthews

Abstract

North Island robins (*Petroica australis longipes*) and North Island tomtits (*Petroica macrocephala toitoi*) are among the non-target animals at risk during poison-based control operations aimed at introduced mammalian pests in New Zealand. Adding an avian repellent to bait may reduce the risk to native birds. In this study, the feeding behaviour of robins and tomtits towards baits treated with bird repellents was measured. In Experiment 1, wild robins and tomtits were trained to approach observers and were offered repellent-treated (blue colour + 2% Avex) and standard (green colour + cinnamon oil, as used for pest control operations in New Zealand) dough baits, in choice tests over four days on a test arena on the forest floor. Robins pecked at standard baits more frequently than repellent baits, with the frequency of pecking at repellent bait remaining very low over the four days. Robins occasionally removed baits of either type from the arena, but consumed only standard bait. In contrast to robins, tomtits never pecked at either bait type or removed bait from the arena. Tomtits also spent significantly less time on the arena than robins. Because tomtits never interacted with baits in Experiment 1, an alternative 'throw' test was used to offer robins and tomtits repellent and standard baits of two types (carrot and dough) in Experiment 2. Individual repellent and standard carrot or dough baits were thrown (at 30s intervals) onto the litter arena by the observer and the response of the birds to each bait (ignore, investigate, peck) was recorded. Robins investigated more than 90% of all baits thrown, but pecked almost exclusively at standard baits (88% of pecks): the repellent effectively

deterred robins from feeding. Robins also pecked at more dough than carrot baits. Tomtits ignored over 89% of baits, and never pecked at any of the thrown baits. They investigated more standard baits (16% of baits thrown) than repellent baits (6% of baits thrown), but there was no difference in the rate of ignoring, investigating or pecking for carrot or dough baits. These results clearly indicate a difference in the feeding behaviour of robins and tomtits towards baits, and may reflect differences in their preparedness to feed from the ground or to feed on novel food types. Tomtits may be less likely than robins to eat baits in some circumstances. Further research will be required to clarify whether primary or secondary poisoning is responsible for tomtit mortality during pest control operations, and therefore, whether bird repellent baits would afford tomtits any protection.

Keywords: bird repellent; feeding behaviour; North Island robin; North Island tomtit; pest control.

Introduction

In New Zealand, aerial poisoning operations with carrot or cereal baits containing sodium monofluoroacetate (compound 1080) are used widely to control introduced mammalian pests, such as brushtail possums (*Trichosurus vulpecula*) and ship rats (*Rattus rattus*). Control operations are conducted primarily to protect native species and ecosystems, and to prevent the spread of bovine tuberculosis (*Mycobacterium bovis*) to cattle and deer herds on adjacent farmland. Effective pest control operations have significant conservation benefits, and it is generally assumed that the benefits of pest control outweigh the risks to non-target native species (Spurr, 1991).

Poison-based pest control has caused some mortality of non-target native bird species (Spurr, 2000). Poisoning may be primary (e.g. robins directly eating toxic cereal or carrot bait; Spurr and Powlesland, 1997), or secondary (e.g. morepork, *Ninox novaeseelandiae*, eating invertebrates or the carcasses of rodents that have fed on baits; Spurr, 2000). Non-target mortality is a significant factor reducing the acceptability of pest poisoning operations to the public (Fitzgerald *et al*, 2000). By reducing non-target bird mortality during pest control, populations may recover more quickly and

successfully and pest control practices may be considered to be more ethically acceptable.

Ground feeding birds, such as robins and tomtits (*Petroica macrocephala*) are particularly vulnerable to poisoning (Brown, 1997; Empson and Miskelly, 1999; Powlesland *et al*, 1999). Both are member of the family Eopsaltriidae, of which there are three species endemic to New Zealand. Robins are small (18cm, 35g) territorial forest passerines. Their diet consists mainly of invertebrates, supplemented by small fruits in summer and autumn (Heather and Robertson, 1996). They feed predominantly on the forest floor by gleaning invertebrates from the leaf litter and rely largely on sight to find their prey (Powlesland, 1981). Robins will sometimes tremble a foot to induce invertebrates to move in response to the vibrations (Heather and Robertson, 1996). Robins have previously been observed eating cereal and carrot baits (Chapter 3; Day *et al*, 2003; Spurr and Powlesland, 1997), and it is assumed most robins die from primary poisoning (Spurr, 2000). The most significant impacts on robins have been observed during carrot-based operations where small bait fragments (chaff) have been accidentally distributed (Powlesland *et al*, 1999), although similar levels of mortality have been observed during cereal–based control using Talon 20P (Brown, 1997).

Tomtits are smaller than robins (13cm, 11g), but are similar in many aspects of their breeding biology, habitat preferences and diet. Tomtits will live in more open forest or scrub than robins and forage from ground level to the top of the canopy (Heather and Robertson, 1996). Like robins, they feed mainly on invertebrates, supplemented by small fruits in summer and autumn (Heather and Robertson, 1996). Tomtits use a 'watch and wait' feeding strategy, usually perching above the ground and scanning a branch or the ground for invertebrate movement, then flying down to capture their prey (Gibb, 1961). Tomtits do not usually turn over or search through leaf litter for prey like robins or blackbirds (*Turdus merula*) do (Gibb, 1961), and spend only short periods of time on the ground. It has not been determined whether tomtits are poisoned via primary or secondary poisoning (Powlesland *et al*, 2000). During control operations, tomtit mortality appears to be highest during carrot operations, and low or nil during cereal operations (Powlesland *et al*, 2000; Westbrooke *et al*, in prep.). However, in carrot-based control operations, baits are generally sown at higher application rates than cereal operations, so it is yet to be determined whether tomtits would be killed during low sowing rate carrot operations (Westbrooke *et al*, in prep.).

Procedures to reduce the poisoning of birds such as robins and tomtits include removal of all small bait fragments that can be readily manipulated by the birds, dying all baits green (a colour initially believed to be unattractive to birds; Caithness and Williams, 1971), adding cinnamon oil as a bird deterrent, and reducing bait application rates on the assumption that fewer bird-bait encounters will occur. Unfortunately, native birds still die during pest control operations that use large green-dyed, cinnamon-flavoured baits (Spurr, 2000). Therefore, recent research (e.g. Spurr and Porter, 1998, Spurr *et al*, 2001) has focused on baits or bait additives that may effectively repel non-target birds while remaining attractive to pest species such as brushtail possums and rats. For example, Spurr and Porter (1998) found that cinnamamide deterred weka and kea from eating baits without affecting bait acceptance by possums. Unfortunately, bait acceptance by rats was reduced and the compound is relatively expensive, so its use has not been explored further. All other repellents tested thus far have also been rejected for use in pest control baits because they were either too costly or had deleterious effects on bait consumption by target pests.

Wild robins have proved to be an ideal species for evaluating repellents in the context of pest control in New Zealand, as they respond positively towards humans and will approach to take food (Maloney and McLean, 1995). Robins have strong colour preferences, with birds preferring red and yellow coloured food over green or blue food (Hartley *et al*, 1999). Furthermore, blue coloured food is less attractive to robins than green (Hartley *et al*, 1999), is accepted by pests (Day and Matthews, 1999) and offers potential as a cue to deter robins from baits. However, in many species, including robins, lowly preferred bait colours alone do not provide a long-lasting deterrent effect (e.g. Chapter 4; Hartley *et al*, 1999), so must be combined with other cues to be effective. Day *et al* (2003, Chapter 3) found that wild robins were deterred from feeding on baits treated with the combination of a primary repellent (2% d-pulegone) and secondary repellent (2% Avex, an anthraquinone-based product). D-pulegone acts via strong olfactory and taste cues (Mason, 1990), and may have acted as a salient cue for a learned aversion caused by the anthraquinone (Day *et al*, 2003, Chapter 3). Robins were also strongly deterred by an alternative repellent combination of blue colour + 2% Avex (Chapter 5). Research with house sparrows (*Passer domesticus*) suggests that the repellent effects of 2% Avex are significantly improved by the addition of the blue colour (Chapter 4). This combination has

significant promise for protecting birds during pest control operations (Chapter 5) and was readily accepted by the target pest species, brushtail possums and ship rats in captive trials (Day *et al*, 2000).

   The current study aimed to compare the feeding behaviour of wild robins and tomtits when presented choices between repellent (blue colour + 2% Avex) and standard (green + cinnamon oil) baits. We used a test method established with robins (Day *et al*, 2003, Chapter 3; Chapter 5) to present the baits to trained wild robins and tomtits and also developed and tested an alternative method for presenting the baits. Choice tests were used so we could easily compare the relative response of each bird to repellent and standard baits. The alternative method was developed to try and induce more bait investigation from the test birds, particularly tomtits. The baits presented were similar to those tested previously with robins on Tiritiri Matangi Island (Chapter 5). In the current study, we used a mainland population of robins and tomtits and tested the baits at a different time of year. Although tomtits are very similar to robins in many aspects of their biology, there appear to be differences between tomtits and robins in their susceptibility to poisoning in some control operations (described above). We considered that subtle differences in the feeding behaviour of tomtits and robins may alter the ability of repellents to protect them from poisoning. Therefore, we decided to compare the efficacy of repellent-treated baits simultaneously for both species.

Methods

The experimental protocols were approved by an independent Animal Ethics Committee (Ruakura AEC approval 3136) and were conducted under a permit from the New Zealand Department of Conservation.

Subjects

Nine wild robins (four female, five male) and nine wild tomtits (six male, three female) living in the Waimanoa study area, Pureora Forest Park were used in this experiment in March 2002. The study site was previously used in August 1997 to assess the impact of 1080-based aerial pest control, using carrot baits, on robins (Powlesland *et al*, 1999) and tomtits (Powlesland *et al*, 2000). No pest control had been conducted since the 1997 operation. Five of the robins and one of the tomtits

had been captured during the previous three breeding seasons and fitted with leg bands for identification by Department of Conservation staff. It is not known if the individual robins or tomtits were present during the 1997 pest control operation (they were not captured or banded during the routine bird surveys of the area pre- or post control), but it is possible based on their lifespan that some adult birds may have been present.

Each robin and tomtit was trained to approach an observer. As robins and tomtits are inquisitive, they naturally approach people that enter their territories (Heather and Robertson, 1996). Mealworm larvae (*Tenebrio* spp) were fed to these robins and tomtits while the observer tapped on the lid of the mealworm container. The noise was made so that robins and tomtits associated it with being fed and thereby learned to approach the observer in future. This training procedure has been used routinely for robin (Armstrong *et al*, 2000) and tomtit (Powlesland *et al*, 2000) monitoring in the past. All birds used in this study had been approaching the observer regularly for at least a week prior to the experiment.

Baits used

In Experiment 1, we used baked, lard-based dough as our bait, following the recipe of Day *et al* (2003, Chapter 3). Dough bait was chosen as a carrier for the repellent in this experiment, as we had previously demonstrated this to be a highly preferred bait material for robins (Day *et al*, 2003, Chapter 3), and using a preferred bait material gave us a conservative test of repellent effects. The dough was chopped into approximately 5-mm cubes after baking, a size which could be readily manipulated by robins (Hartley *et al*, 1999). Although it had not previously been demonstrated, we assumed that the dough baits would be similarly attractive to tomtits, based on the similar feeding behaviour of both species. Two dough bait types were made: standard bait and repellent bait. The standard bait recipe contained green dye (0.01% wt/wt; Special Green V200A dye, Bayer NZ Ltd, Auckland) and, after being baked and chopped, was surface coated with a solution of water containing 0.1% cinnamon oil (Bush Boake Allen Ltd, Auckland). The cinnamon was added to the baits by "dipping" the chopped dough into the treatment solution in sieves (solution volume was 10% of total bait weight, baits dipped for 60sec), and then allowing the pieces of dough to air-dry (for 8hr) before sealing them in airtight containers. The green-

cinnamon standard bait represented the typical bait used currently for pest control in New Zealand. The repellent bait recipe contained blue dye (0.01% wt/wt; Royal blue permanent colour powder H6406, International Flavours and Fragrances, Auckland, New Zealand) and, after being baked and chopped, was surface coated with a solution of water containing 2% Avex (50% wt/wt 9,10-anthraquinone; CAS No. 84-65-1). The solution was added to the baits in the same manner as for standard baits (solution volume was 10% of total bait weight, baits dipped for 60sec).

In Experiment 2, we used the same standard and repellent-treated dough baits as in Experiment 1, as well as standard and repellent-treated carrot baits. The carrot baits were surface coated with solutions containing the same dyes and chemicals (at the same concentrations) as used in Experiment 1.

Experiment 1

We used the method of Day *et al* (2003; Chapter 3; Chapter 5) to offer the robins and tomtits choices between repellent and standard dough baits. A test arena, consisting of a 0.75m x 0.50m area scraped clear of leaf litter, was set up centrally in each robin or tomtit territory over four days. A new arena, within 5m of the previous day's, was used each day. Two teaspoon-sized piles of each bait type (~20g) were placed side-by-side in the middle of the test arena, with each pile 25 cm apart. The position of each bait type on the arena was alternated for each bird each day to remove any position biases. Birds were attracted to the test arena by the observer tapping on a plastic container. Once the subjects were within 3m, a single mealworm was tossed into the test arena. This stimulated the robins and tomtits to alight in the arena and eat the mealworm. While on the arena birds had the opportunity to eat other invertebrates and investigate the baits. Robins and tomtits showed considerable interest in the test arena, as clearing the leaf litter exposed invertebrates that the birds foraged for. Birds were offered dough baits in the test arena for 25 minutes (timed from the first bird encounter after the arena was set up) per day (between 0600 h and 1600 h), over four days. Not all birds were present every day, so the four exposures to bait were presented over an 8-day period.

We used a video camera (Sony TRV310E Digital Handycam) to record the feeding behaviour of each bird on the arena during each 25-minute exposure. The camera was mounted on a tripod 1.5m above the ground and was positioned 2-3m from the

arena, so that the entire arena could be seen. In subsequent analyses of the videotapes, we recorded the total amount of time each bird spent on the arena. Every peck directed towards each type of bait was recorded (using slow-motion playback where necessary). A peck was defined as every contact made by the birds' beak with one of the baits. Although only one observer conducted the analyses from the video tapes, we used a second observer to determine inter-observer reliability for the pecking data. Using 10 randomly chosen test periods, the inter-observer reliability for the peck frequency (expressed as the Pearson correlation coefficient) was $r = 0.94$ ($n = 10$, 8 d.f.). If a bird removed one of the baits from the test arena (i.e. picked it up in its bill and flew away with it), the type of bait removed (standard or repellent) and the subsequent fate of the bait (eaten, dropped or taken out of sight) was recorded.

Experiment 2

The robins and tomtits that had been offered baits in Experiment 1 were used in Experiment 2, one week later. The same birds were used because there were too few birds available in the study area to train new robins and tomtits specifically for this experiment. As in Experiment 1, a test arena was set up centrally in each robin or tomtit territory each day. Birds were attracted to the test arena by the observer tapping the plastic container and offering each bird a single mealworm. Once the birds had been on the arena at least once (usually to pick up the mealworm), they were immediately offered baits. Baits were offered to the birds by 'throwing' individual bait pieces onto the arena at 30 second intervals. Twenty baits were offered to each bird per day (five bait pieces each of standard carrot, repellent carrot, standard dough and repellent dough). The order in which the 20 baits were presented to the birds was randomised for each bird each day. The birds were offered baits between 0600 h and 1600 h each day, with each bird being given up to four once-daily exposures to bait over a four day period (mean of 2.9 ± 0.4 exposures per bird).

   We used a video camera, in addition to observations conducted during tests, to record the feeding behaviour of each bird during the tests. The camera was mounted on a tripod 1.5 metres above the ground and was positioned 2-3 metres from the arena, such that the entire arena was recorded. Prior to throwing each bait, we estimated the perching height (on ground, <1m, 1-2m and >2m above ground) of each bird. For each bait that was thrown into the arena we used a categorical ranking

to score the behaviour of the bird as either: (1) Ignore – the bird did not turn its head towards the bait, look at the bait, or show any observable behaviour to indicate that the bait had been seen; (2) Investigate – the bird turned its head towards the bait, appeared to look at the bait or ground where the bait was thrown to, and may have flown from its perch towards the bait or arena, but did not peck at the bait or ground beside the bait; or (3) Peck – the bird approached the bait (as in (2) above) and pecked at it at least once, appearing to make contact with the bait with its bill (the bird then sometimes ate some of the bait). We recorded on data sheets the highest numerical category response displayed over each 30 second period, prior to throwing the next bait. If a bird pecked very close to the bait, but it was uncertain whether the bird had made contact, we still recorded the response as a peck. Each peck response was then re-examined on the video tapes, and if any birds recorded as pecking had not made contact with the bait with their bills (this can be difficult to determine during direct observation), the response was re-categorised as an 'investigate' (see above).

Data analyses

In Experiment 1, the number of pecks made at the two bait types were analysed as Poisson variates using the General Linear Mixed Model (GLMM) in the Genstat 6.1 statistical package (Lawes Agricultural Trust, Rothamsted Experimental Station, Hertfordshire, United Kingdom). A fixed effect for bait type was retained throughout analysis. Terms for location, date, bird by bait and bird by date were retained if statistically significant at the 5% level, but that for bird was retained regardless of statistical significance. The level of significance for any fixed effect was obtained by calculating an F-ratio from the related Wald statistic. The means we present were back-transformed and re-scaled from the Poisson model. Standard errors for each mean reflect the average change resulting from the addition and subtraction of standard errors on the transformed scale. The time spent on the arena during each test session was analysed for robins and tomtits using ANOVA. The number of pieces of bait of each type removed (and their subsequent fates) were compared using Chi-square tests.

In Experiment 2, the percentage of responses of each type (ignore, investigate or peck) towards baits were analysed as Poisson variates using the General Linear

Mixed Model (GLMM). Robin and tomtit data were analysed separately. Fixed effects included bait type, base material and day of presentation. Terms for date, bird by bait type, bird by base material and bird by date were retained if statistically significant at the 5% level, but that for bird (the individual used) was retained regardless of statistical significance. The level of significance for any fixed effect was obtained by calculating an F-ratio from the related Wald statistic. Means presented were back-transformed and re-scaled from the Poisson model.

Results

Experiment 1

All robins and all tomtits ate the single mealworm that they were offered at the beginning of the test period on every day that they were present. Not all birds were present every day, but on average, robins were given the same number of exposures to baits (mean of 3.2 ± 0.4) as tomtits (mean of 3.1 ± 0.3; $F_{1,16} = 0.06$, $P = 0.807$). To eat the mealworm offered, each individual had to fly down to the test arena to pick the mealworm off the ground with its bill. Most robins then began foraging on the arena by moving leaf litter with their bill and/or trembling a foot. Robins hopped around the arena pecking at invertebrates detected and when they left the arena either hopped along the ground or flew to a close perch.

Tomtits did not forage on the arena immediately after feeding on the mealworm and always flew from the arena and perched on a nearby branch. All tomtits returned to the arena at least one further time during each exposure period to capture other prey items exposed by the initial scraping back of the leaf litter. Robins spent significantly longer on the test arena during each test period (mean of 9min 3sec $\pm$ 44sec) than tomtits (mean of 1min 39sec $\pm$ 11sec; $F_{1,55} = 95.76$, $P < 0.001$). There was no change in the time spent on the test arena across repeated exposures for either robins ($F_{3,25} = 0.015$, $P = 0.997$) or tomtits ($F_{3,24} = 0.178$, $P = 0.910$).

Despite regularly flying down to the arena and readily accepting the mealworm offered, tomtits never pecked at or removed any baits of either type in Experiment 1. In contrast, robins readily pecked at standard dough bait throughout the exposures (Figure 1). Robins pecked at repellent bait infrequently, and significantly less than at

standard bait on all days ($F_{1,25}$ = 59.71, P < 0.001; Figure 1). There was no change in the pecking frequency of robins towards standard or repellent baits across days ($F_{3,25}$ = 1.306, P = 0.295). Robins removed some baits from the test arena, and removed more standard baits than repellent baits (see Totals, Table 1). When the fate of bait removal was determined, robins usually ate standard baits and dropped repellent baits (χ^2 (2 d.f.) = 6.5, P = 0.039; Table 1).
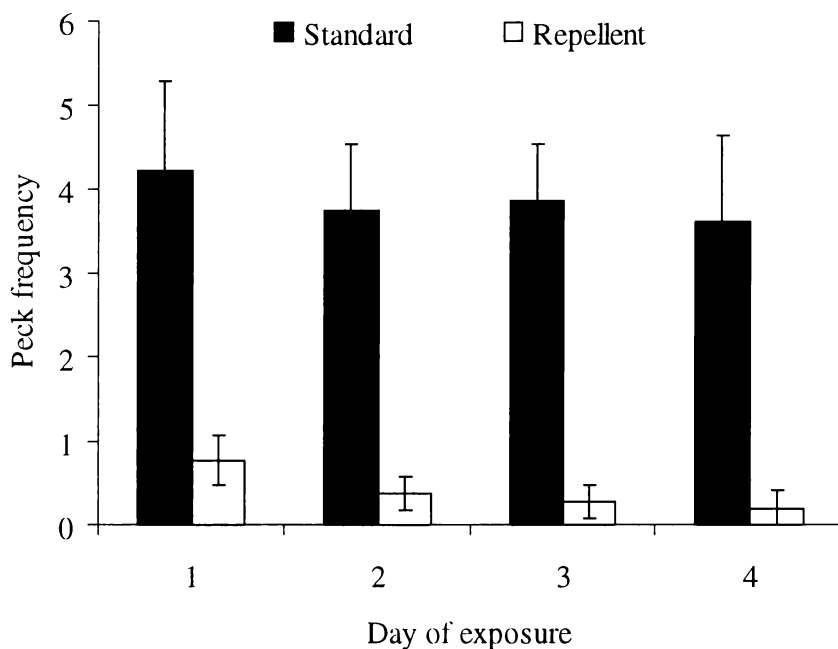
Figure 1:   *Adjusted mean number of pecks (± SE) by robins directed at standard or repellent dough baits over four days of exposure in Experiment 1.*

Experiment 2

As in Experiment 1, robins and tomtits always readily ate the mealworm offered to them just before the test period on every day. After eating the mealworm robins hopped around the arena pecking at invertebrates and if they left the arena either hopped along the ground or flew to a close perch and waited for the next bait to be thrown (43% of perching observations were at ground level and another 50% of perches were between ground level and 2m from the ground, Table 2; range 0.1m – 5m). Tomtits occasionally foraged on the arena after feeding on the mealworm, but usually flew and perched on a nearby branch (2% of perches were at ground level

and another 73% of perches were between ground level and 2m from the ground, Table 2; range 0.5m - top of canopy).

Table 1:   *Total number of standard and repellent baits that were eaten, dropped or taken out of sight (unknown fate) by robins when they removed baits from the test arena in Experiment 1.*

Fate of bait	Standard	Repellent
Eaten	6	0
Dropped	1	3
Unknown	5	2
Total	12	5

Table 2:   *Use of perches of different heights (% of observations) by robins and tomtits during the throw test in Experiment 2.*

Perch height	Use of perches (% of observations)	
	Robins	Tomtits
Ground level	43	2
> 0 - 1m	34	27
> 1 - 2m	16	46
>2 m	7	25

When the observer threw baits into the test arena, robins initially ignored only 7% of all baits (2% of standard baits, 11% of repellent-treated baits), but by Day 4 ignored significantly more of the repellent-treated baits than they did on Day 1 (11% of repellent baits ignored on Day 1 vs 48% on Day 4; $F_{6,27} = 22.03$, $P = 0.009$;

Figure 2). They also investigated significantly fewer repellent baits over exposures (78% of repellent baits investigated on Day 1 vs 52% on Day 4) and pecked at significantly fewer repellent baits over exposures (11% on Day 1 vs 0% on Day 4). Overall, robins ignored only 2% of standard baits that were thrown (2% of standard carrot baits; 2% of standard dough baits). There was a significant bait type by bird response interaction, with robins pecking at more standard baits (68%) than repellent baits (8%), irrespective of the base material ($F_{2,10} = 91.96$, $P < 0.001$; Figure 2). There was also a significant effect of base material, with robins pecking more dough baits (44%) than carrot baits (32%; $F_{2,186} = 7.80$, $P = 0.022$). No other significant effects were observed.

Tomtits never pecked at any of the baits that were thrown into the test arena. They ignored the majority of baits that were thrown (89% of baits overall, 84% of standard baits, 94% of repellent-treated baits; Figure 3) and the percentage of baits ignored or investigated did not differ between carrot (88%) and dough baits (91%; $F_{1,111} = 1.96$, $P = 0.164$) or across days of exposure ($F_{3,13} = 4.43$, $P = 0.267$; Figure 3). Overall, there was a significant bait type effect, with tomtits investigating a greater percentage of standard baits (16%) than repellent baits (5%; $F_{1,6} = 9.53$, $P = 0.022$, Figure 3).

A) Carrot bait

Percentage of responses to baits

B) Dough bait   ■ Standard   □ Repellent

Figure 2:   *Responses of robins (mean percentage of baits ignored, investigated or pecked) towards standard (solid bars) or repellent-treated (open bars) baits over four days of exposure in Experiment 2, for: A) carrot bait, and B) dough bait.*
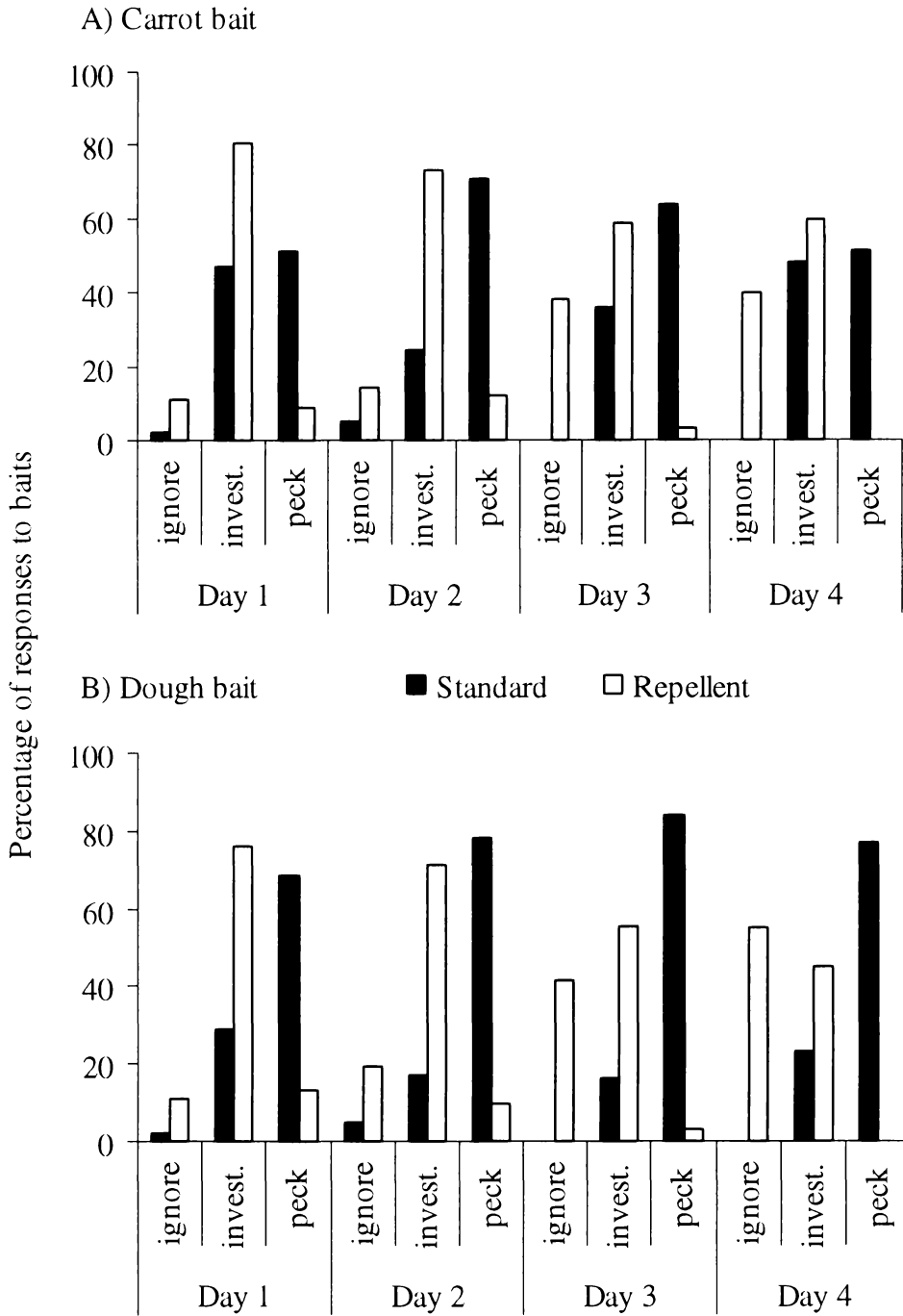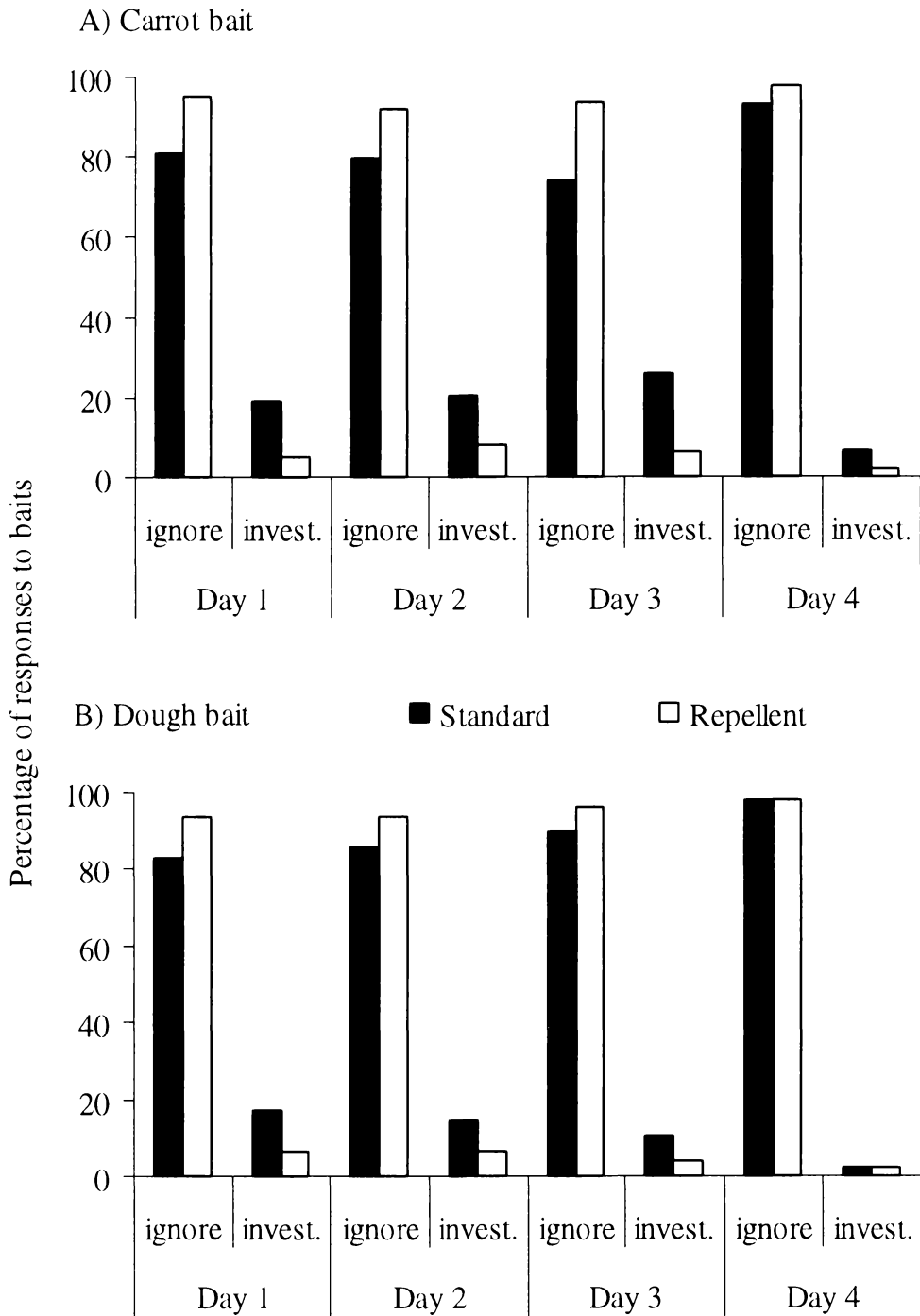
Figure 3:   *Responses of tomtits (mean percentage of baits ignored or investigated)*
towards standard (solid bars) or repellent-treated (open bars) baits
over four days of exposure in Experiment 2, for: A) carrot bait, and B)
dough bait.

Discussion

In this study, robins readily pecked at standard dough baits in Experiment 1 and at standard carrot and dough baits in Experiment 2. This is consistent with previous observations of robins eating green-cinnamon baits (Day *et al*, 2003; Chapter 5; Spurr and Powlesland, 1997). Robins rarely pecked at repellent-treated baits of either bait type in either experiment. In Chapter 5, we have previously found that robins rarely pecked at dough bait treated with blue colour + 2% Avex and pecked less frequently at repellent-treated baits over repeated exposures. In Experiment 1 of this study, we did not observe any decrease in pecking frequency towards repellent-treated baits over exposures. This is most likely because the pecking frequency of robins towards repellent baits was very low on Day 1, so could not decrease significantly more on the subsequent days. In Experiment 2, however, we found that robins altered their behaviour towards thrown repellent baits (carrot or dough) over exposures; they ignored more repellent baits, investigated fewer repellent baits and pecked at fewer repellent baits over exposures. These data indicate similar learning-based behavioural avoidance of blue colour + 2% Avex baits over time that we have observed previously with robins (Chapter 5) and house sparrows (Chapter 4). Others have also found that anthraquinone-based repellents require birds to sample some food before avoidance learning can occur (Avery *et al*, 1997).

Tomtits never pecked at any baits in either experiment, including the standard baits, so it was difficult to determine the effect of the repellent on bait ingestion. However, tomtits investigated repellent-treated baits less frequently than standard baits, suggesting that the repellent may be effective with tomtits as well. Tomtits ignored many more of the thrown baits than robins and investigated far fewer baits, suggesting they were generally much less interested in the baits that robins were. To date, no reports of tomtits feeding directly on baits have been published. Our data suggest that, at least in the circumstances described here, tomtits appear to be less likely to interact with, and eat, baits than robins. However, we have not determined if tomtits will eat baits during normal pest control operations, or if repellents will help to protect tomtits from poisoning.

Robins spent significantly longer on the arena during each test period than tomtits. This was primarily because robins tended to stay on the test arena once on the ground and forage in the leaf litter, whereas tomtits flew to the ground for only short periods

and then perched on a nearby branch scanning the ground for further prey items. This 'watch and wait' feeding strategy has been described previously for tomtits (Heather and Robertson, 1996), and others have also noted that tomtits spend very little time on the ground (Gibb, 1961). Robins will also watch and wait for prey, but they usually actively search for and disturb prey on the ground by turning the leaf litter over with their bill (Powlesland, 1981). When robins left the arena, they either hopped away along the ground or perched less than 2m off the ground. In contrast, tomtits always flew off the arena and perched anywhere from just above ground level to the top of the canopy. These differences between robins and tomtits in their preparedness to use the ground for foraging (Heather and Robertson, 1996) may help to account for the different responses we observed towards baits.

  Several other possibilities exist for the tomtits' lack of interaction with baits in either experiment. It is possible that both the standard and repellent dough and carrot baits were unattractive to tomtits. We assumed that tomtits would be attracted to dough or carrot baits (as we had previously demonstrated for robins), but this may not have been the case. It is possible that the green-cinnamon and repellent-treated baits both deterred tomtits from feeding, or that the baits were not chopped into small enough pieces for the tomtits to manipulate and eat. However, tomtit mortality during poisoning operations has been substantial where small fragments of green-cinnamon carrot baits have been present (Powlesland *et al*, 2000). This mortality could theoretically have been caused by secondary poisoning (e.g. tomtits eating invertebrates that have fed on baits) rather than tomtits eating baits directly, but this does not explain why operations with smaller fragments cause more deaths.

  Both of our test methodologies, while being suitable for robins, may have been inappropriate for evaluating the feeding behaviour of tomtits. Both robins and tomtits were trained to accept mealworms prior to beginning this study, and all individuals regularly ate every mealworm they were offered. While this suggests that the tomtits were familiar with the observer and with being fed, it may have meant that the tomtits were focused on feeding on mealworms, rather than on interacting with alternative baits. For example, the baits may have been relatively much less attractive to tomtits than the mealworms and, therefore, were ignored because the tomtits were waiting for further mealworms. Robins, on the other hand, may not prefer mealworms much more than baits, so continued to eat whichever was offered. We

have not previously found feeding mealworms to affect the feeding behaviour of trained robins (e.g. Day *et al*, 2003; Chapter 5), and trained robins readily ate baits in the current study. We tried to minimise any negative effects of providing mealworms on bait interaction or consumption, by offering tomtits only one mealworm at the start of each test period. This provided them an initial reward for visiting the test arena, but allowed the tomtits plenty of opportunity to interact with the baits. When tomtits are offered mealworms *ad libitum*, they usually consume five or six mealworms before stopping feeding (T. Day, *pers. observation*), so it is unlikely that the birds had been sated by a single mealworm in this study.

  Prey movement may be critical for tomtits to identify food items, as evidenced by their 'watch and wait' feeding style (Heather and Robertson, 1996) and preparedness to rapidly collect mealworm when thrown by an observer (e.g. Powlesland *et al*, 2000). In Experiment 2, we introduced movement to the bait presentations by throwing them into the test arena, in the same manner that we would normally throw mealworms. Tomtits investigated 19% of the standard carrot baits and 13% of standard dough baits, but never proceeded to peck at or eat any piece of bait. Thus, the throwing movement we used was not sufficient to stimulate tomtits to feed on the baits. Mealworms usually continue to wriggle or move once thrown onto the arena, whereas the baits remained static once they had landed. The movement of mealworms once on the arena may have been critical for eliciting a feeding response from tomtits. Overall, tomtits were much less prepared to sample baits than robins were in the same circumstances. Although we have not determined what this result means in terms of poisoning risk during a control operation, it suggests that tomtits may be less likely than robins to eat baits in some circumstances.

  A number of questions remain about the pathways of poisoning for tomtits and we recommend that further experiments are conducted to determine how tomtits are poisoned during control operations. The fact that we observed no direct feeding on baits by tomtits may reflect the method we used to test the baits, but also raises the possibility that tomtits may be killed via secondary poisoning. Both carrot and cereal baits can become covered in invertebrates within a day or two of a poison drop (e.g. Spurr and Drew, 1999), and tomtits readily fly down to capture prey from the forest floor (Gibb, 1961), so could be at risk of foraging on invertebrates present on the surface of baits.

The repellent tested in these experiments effectively deterred robins from feeding on carrot and dough baits. The results were very similar to those achieved previously using birds on Tiritiri Matangi Island (Chapter 5). The current study was conducted in late March and early April, later than the summer experiments and earlier than the late winter experiments we conducted with robins on Tiritiri Matangi Island (Chapter 5), suggesting that the repellent is effective under a range of seasonal and environmental conditions. The standard choice test procedure and the newly developed throw test produced consistent responses from the robins, and either method could be used to evaluate alternative baits in the future. The blue + 2% Avex repellent has now been tested under a range of conditions, consistently achieving high repellency rates for robins. For bird species that eat baits directly, the repellent appears to afford some protection. Further research should determine whether the repellent effects hold for other vulnerable avian species. Field trials are also required to determine the efficacy of repellent baits for bird protection and for achieving high levels of target pest control.

Acknowledgements

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Summary:

This chapter (Chapter 6) replicated aspects of the experiment conducted in Chapter 5. Robins and tomtits were offered a choice between standard and repellent-treated baits (blue colour + 2% Avex) using two test methods. The repellent combination appeared to effectively deter birds, but significant differences were found in the feeding behaviour of robins and tomtits. These differences may reflect differences in the preparedness of each species to feed from the ground or to feed on novel food types. Tomtits may be less likely than robins to eat baits in some circumstances but further research will be required to relate this information to poisoning risk.

The following chapter (Chapter 7) is a general discussion of the results from all experimental chapters in this thesis. It draws together the main results from each experimental chapter to describe the advancement in knowledge that has been gained from these studies, the future research that will be needed, and the practical implications of the work.

Chapter 7

General Discussion

In this thesis, I have investigated the efficacy of repellents for deterring three avian species from feeding, with particular emphasis on deterring native New Zealand birds from feeding on pest control baits. Free-ranging house sparrows, North Island robins and North Island tomtits were offered foods treated with repellents, using a range of methods to determine repellent effects. Initially, I selected several repellents to compare, with each repellent targeting different senses and having primary or secondary modes of action (Chapter 1). Effective combinations of repellents were identified using sparrows (Chapters 2 and 4); the ability of these combinations to deter native birds from feeding was then compared to standard pest control baits for robins (Chapters 3, 5 and 6) and tomtits (Chapter 6). I identified two combinations of repellents that may reduce the risk of poisoning for non-target birds in a cost-effective way and made several other important findings.

In this chapter, I synthesise and discuss the results from all of my experiments. The efficacy of each repellent and combination evaluated with each species is described and I discuss how these results relate to previous literature. This discussion identifies further avenues for the development of effective combinations of repellents and considers the variability of repellency within and between avian species. The experimental methods and species used are also compared, and their suitability for my studies and future work are discussed. I close the discussion with comments on how the findings of my research may be used to help ensure fewer non-target native birds are poisoned during vertebrate pest control operations.

Efficacy of individual repellents

I chose to determine the efficacy of five potential repellents for deterring sparrows from feeding: neem oil, agricultural lime, d-pulegone, Avex and blue colour. In Chapter 2, I found that two primary repellents (neem oil and agricultural lime) did not greatly reduce house sparrows' consumption of treated wheat. In choice tests,

sparrows appeared to eat plain wheat before they ate wheat treated with either repellent, but once the plain wheat was mostly eaten, they rapidly consumed all concentrations of each repellent treatment. Neem oil and lime-treated wheat were usually fully consumed within 8hr of presentation. There was no evidence that either repellent was actually aversive or distasteful to birds over more than a few minutes or hours. The initial delay in feeding may have simply reflected a general preference for plain wheat, or a neophobic response towards the novel visual, olfactory and taste cues presented by the repellent treatments. My experimental design did not allow me to differentiate between preference and neophobia, but if unlimited quantities of all wheat types were provided in a future study, it may be possible to accurately determine preference. Previous researchers have found neem oil (Mason and Matthew, 1996) and agricultural lime (Belant et al, 1997; Clark and Belant, 1998) to be effective repellents for other bird species at similar concentrations. However, neither of these repellents has been proven (because experiments have not been conducted or published) to be effective with the wide range of avian species and feeding situations that are typically demonstrated for highly effective repellents (e.g. anthraquinone; see Avery et al, 1997; 1998). It is possible that either of these repellents may have been effective under different test conditions (e.g. different test methods, higher repellent concentrations, fewer sparrows feeding on each table), or with alternative species, but I concluded that the almost complete lack of avoidance by birds meant that neither repellent warranted any further investigation in my thesis.

In contrast to neem oil and agricultural lime, the other primary repellent (d-pulegone) effectively reduced sparrow feeding (Chapter 2). Typical of an effective primary repellent, consumption of 0.5% to 2% d-pulegone-treated food was significantly reduced over the first few exposures. There was little evidence of habituation or greater avoidance of repellent-treated food over time. However, the 4 day test period may have been too short to demonstrate habituation or a learned avoidance response. The highest concentration of d-pulegone (2%) was most effective, but only suppressed wheat consumption by about 50%. I did not identify the specific cues that mediated the repellency, but others have demonstrated that both the volatile odours (Wager-page and Mason, 1996) and taste or irritant cues (Mason, 1990) of d-pulegone are important in repellency. Post-ingestional illness, including vomiting, has been observed in one study of birds fed d-pulegone-treated food

(Mason, 1990), but no other similar observations have been reported in other research with d-pulegone. My observations and the pattern of food consumption I recorded provided no evidence of any post-ingestional illness or subsequent learned avoidance response. If sparrows had developed a learned avoidance towards d-pulegone-treated wheat in my study, I would have expected to observe a reduction in treated wheat consumption over days, as was observed for Avex (see below).

Avex, the anthraquinone-based secondary repellent I evaluated, also reduced food consumption by sparrows (Chapter 2). When I first offered Avex-treated wheat to sparrows (Chapter 2, Experiment 1), they initially ate most of the Avex-treated wheat, but progressively ate less of the treated wheat each day. The pattern of wheat consumption was consistent with other studies, which have found that birds exhibit no immediate aversion to anthraquinone-treated foods but are subsequently repelled (Avery *et al*, 1997; Dolbeer *et al*, 1998). This pattern of consumption has led to suggestions that anthraquinone acts via secondary repellency, with birds learning to avoid the treated food only after a negative post-ingestional experience (Avery *et al*, 1997). I did not conduct any observations to measure post-ingestional illness in this thesis, so cannot confirm whether Avex had this effect on any of the birds tested.

In subsequent presentations of Avex-treated wheat on the sparrow feed tables, the pattern of Avex-treated wheat consumption observed differed slightly from the pattern recorded during the initial presentation. I found in the subsequent exposures that Avex-alone treated wheat caused a reduction in food consumption at first exposure (Chapter 2, Experiment 2; Chapter 4; Experiment 1), with consumption of the treated wheat remaining consistent across days. It is possible that there may have been some carry-over effect from the first experiment, with birds that had learned to avoid Avex-treated wheat when it was first presented, continuing that avoidance in the following experiments. Alternatively, if more birds had been present at each table during subsequent experiments, the pattern of wheat consumption typically observed for learned avoidance may have been masked by continued sampling from new birds each day. This effect was noticed in another study, when an anthraquinone-based repellent was applied to a heavily predated crop (Avery *et al*, 2000). In my study, there was no evidence that sparrows habituated to the Avex alone-treated wheat over periods of up to 10 days (Chapter 2). If Avex had been acting as a primary repellent, I

would have expected to see evidence of habituation over time, as is typical for many primary repellents (e.g. colour alone; Chapter 4).

In Chapter 4 (Experiment 2), I found that a novel colour (either blue or green) elicited strong avoidance responses by sparrows at first exposure, with no consumption being recorded for wheat treated with either novel colour on the first day. Blue colour has previously been found to deter several avian species from feeding, including sparrows (Gionfriddo and Best, 1996; Greig-Smith and Rowney, 1987; Pawlina and Proulx, 1996), robins (Hartley *et al*, 1999) and weka (Hartley *et al*, 2000). However, in my study, colour alone did not elicit long-lasting avoidance responses. Within eight days, sparrows were fully consuming all wheat that had been coloured green or blue. Other birds, such as robin (Hartley *et al*, 1999) and weka (Hartley *et al*, 2000) also readily habituate to foods associated with lowly preferred colours (like blue), unless they possess other repellent characteristics. Therefore, while colour alone would be unsuitable as a repellent to deter birds from eating pest control baits, I considered it may be an effective cue for enhancing the repellency of additional chemicals.

Efficacy of repellent combinations

Although some of the individual repellents tested may have been effective for deterring birds from eating, I chose to evaluate whether combinations of repellents with different modes of action would be more effective than single repellents. Birds sometimes habituate to primary repellents (Chapter 4; Clark, 1998), and, in the context of deterring birds from eating pest control baits, this could leave them susceptible to poisoning. Secondary repellents require bait ingestion prior to avoidance learning, posing a risk to birds of poisoning before the repellent has even taken effect. Further, evidence from previous studies has demonstrated the enhanced efficacy that may be gained by combining salient primary cues with secondary repellents. For example, several researchers have used odours, visual cues or other chemicals to increase the speed of learning towards secondary repellents (e.g. Avery and Mason, 1997; Avery and Nelms, 1990; Greig-Smith and Rowney, 1987; Nelms and Avery, 1997). If the rate of learning could be enhanced by an additional cue, this

may afford better protection to birds during pest control operations; they may learn to avoid baits before they are lethally poisoned.

I found that combinations of a secondary repellent (2% Avex) with either a repellent olfactory/taste cue (2% d-pulegone) or a repellent visual cue (novel blue colour) were highly effective feeding repellents for sparrows (Chapters 2 and 4) and robins (Chapters 3, 5 and 6). Both combinations were significantly more effective than Avex alone for sparrows (this comparison was not made for robins). Anthraquinone-based repellents have been claimed to contain ultra-violet cues that birds are sensitive to (e.g. Ballinger, 1999, 2001), but experimental evidence demonstrating that birds use ultra-violet cues to avoid anthraquinone is lacking. No matter what cues sparrows used to avoid Avex alone-treated wheat, the provision of additional olfactory/taste or visual cues in my experiments (Chapters 2 and 4) appeared to provide extra sensory information that enabled the birds to form strong avoidance responses. Food treated with the combinations of repellents was consumed much less readily at first exposure than plain wheat and subsequent food consumption remained constant or declined further over time in my experiments. This pattern of consumption suggests that the combinations elicited both primary and secondary repellency.

There was no difference in efficacy between 2% d-pulegone + 2% Avex and blue colour + 2% Avex (Chapter 4), suggesting that, at the concentrations used, these different types of cues (olfactory/taste, or colour) were equally appropriate for eliciting avoidance responses. Blackwell *et al* (1999) found that Flight Control, another anthraquinone-based product, was more effective for deterring Canada geese when paired with a visual cue than when used alone. The role of visual cues in enabling many bird species to discriminate between palatable and repellent foods has been demonstrated previously (e.g. Avery and Mason, 1997; Mason and Reidinger, 1983; Nelms and Avery, 1997), so the fact that colour acted as an effective cue in this study is not surprising. Odour cues have also been demonstrated to readily modify feeding behaviour. Roper and Marples (1997) demonstrated that some novel olfactory cues (e.g. almond) can enhance conditioned food avoidance learning in domestic chicks. They also found that effective olfactory cues can exert more powerful control over feeding behaviour than visual cues in some circumstances. Further investigation of the relative merits of using different types of odours and/or visual cues to enhance secondary repellent effects is warranted.

Some of the repellent combinations I tested, however, were not as effective as others for deterring birds from feeding (Chapter 4). Olfactory/taste cues with relatively little previously demonstrated repellency (e.g. cinnamon oil) were apparently not as effective as those with demonstrated aversive properties (e.g. 2% d-pulegone, blue colour). Although the addition of a novel odour cue can enhance avoidance learning in birds, it appears that not all odours are equally efficacious (e.g. Roper and Marples, 1997). Several possibilities exist for why cinnamon oil was ineffective for enhancing repellency in my research. The cinnamon may not have been a highly detectable cue for sparrows or may not have been an effective repellent in its own right, but my experimental design did not allow me to test these options. The concentration used was the same as that used during pest control operations, and I found cinnamon oil did not function as an effective deterrent for robins at this concentration in Chapters 3, 5 and 6. Cinnamon oil may have been effective as an enhancing cue, or as a repellent in its own right, if the concentration used had been higher. There is mixed evidence about the effectiveness of cinnamon for suppressing feeding by birds (e.g. Hickling, 1997; McLennan *et al*, 1992; Spurr, 1993). The results of my thesis, while not testing cinnamon in its own right, suggest that cinnamon is only a weak cue or repellent for the species I tested. These data highlight the necessity to carefully select primary repellents or cues (which alone are detectable, memorable, or reduce the feeding behaviour of birds) that can be coupled with an effective secondary repellent. A further study is warranted, to test whether the most appropriate cues for enhancing secondary repellent effects are cues with primary repellency in their own right (as opposed to salient cues that have no repellency of their own).

There are several avenues for further advancing the development of combinations of repellents. Obviously, some of the repellents that I chose to study were reasonably effective in producing avoidance responses by birds. Further research investigating other concentrations, colours and combinations of these repellents may identify repellents that completely prevent feeding. This research could also focus on the mechanisms by which each component acts to cause repellency and the sensory abilities of the target bird species. Avery (1997) suggested that a better understanding of the perceptual capabilities and sensory systems of the bird species being managed may lead to more effective repellent design, because stimuli that have maximal detectability, discriminability and memorability for the target animal would then be

used. However, further research is required to demonstrate whether using stimuli that provide maximal sensory information will, in fact, influence repellent effectiveness.

A number of alternative repellents (e.g. more cost-effective alternatives) could also be incorporated into repellent combinations and tested. I did not explore the use of irritant cues for repellency in my thesis, although agricultural lime (which was ineffective in Chapter 2) is reported to have some irritant properties (Clark and Belant, 1998), and d-pulegone is also suspected to provide some sensory irritation to birds (Mason, 1990). Chemical irritants provide highly aversive cues that cause primary repellency (Clark, 1998). It is possible that these cues may also speed formation of a learned avoidance response towards a paired secondary repellent. Additionally, many irritants (e.g. methyl anthranilate) also possess other olfactory and taste properties which may be important in the avoidance response (Clark, 1996).

Alternative anthraquinone formulations (e.g. Flight Control; Dolbeer *et al*, 1998), or other secondary repellents (e.g. methiocarb; Mason and Reidinger, 1983) could be tested for efficacy in a primary plus secondary repellent combination. A number of chemicals could be used as a substitute for d-pulegone, and may also prove to be effective as primary repellent cues. Mason and Primus (1996) demonstrated that dl-pulegone (a menthone derivative very similar to d-pulegone) was as effective as d-pulegone for deterring feeding by starlings. Pennyroyal oil, from which d-pulegone is derived, provides a similar level of feeding suppression for red-winged blackbirds as d-pulegone (Avery *et al*, 1996). Both dl-pulegone and pennyroyal would be more cost-effective than d-pulegone if they proved to be effective at similar concentrations. There are obviously also many other potential options for combining repellents, but it is time consuming, labour intensive and expensive to test all possible combinations and concentrations. I believe this has been a significant limiting factor in the development of repellent technology and why many studies, including those in my thesis, have not addressed all possible options. I chose to focus on combining only a few repellents in this thesis, but this does not mean that other combinations would not be equally effective.

Variability of repellent effects

An important concept in repelling birds from feeding is that of variability, both in terms of the responses of individual birds in a population and differences between species. It would be highly desirable to identify repellents that deter all birds in a population and all species that need to be repelled, with little variability in the level of repellency achieved. For sparrows (Chapters 2 and 4), I did not measure the feeding behaviour of individual birds, so I have little data on variation in repellent effects between individuals. However, for repellents that suppressed feeding by sparrows to the greatest degree (e.g. < 10% of blue colour + 2% Avex-treated wheat was consumed; Chapter 4) it is obvious that variability was low, as very few sparrows sampled the treated wheat. For robins, however, it was apparent that even the most effective repellent combination (blue colour + 2% Avex) appeared to vary in its ability to reduce bait exploration and consumption by individual birds. Blue colour + 2% Avex almost entirely prevented bait sampling by the vast majority of robins (Chapter 5). However, a small number of juvenile birds were prepared to peck at and eat the bait significantly more than other robins, and (based on the quantity of bait they appeared to ingest) these birds would probably have been poisoned during a control operation. The same birds also pecked more frequently at the non-repellent standard baits.

Variability between individual birds in feeding choices and response levels have been described before. Anthraquinone caused variable levels of repellency for individual red-winged blackbirds, with a small proportion of individuals appearing to eat much more than all other birds (Avery *et al*, 1998). Hartley (1999) found significant variability in the colour preferences of individual robins and weka and similar results have been observed in colour preference studies with other species (e.g. Northwestern crows; Willson and Comet, 1993). However these studies did not investigate factors about the birds (e.g. age, previous experience, gender) that may have contributed to this variability. In another study, avoidance of colours was found to vary between male and female northern bobwhites (Mastrota and Mench, 1994), but no age, gender or experience effects were observed in a follow-up experiment (Mastrota and Mench, 1995). Therefore, while an effective repellent may deter most individuals from feeding, it may be unrealistic to expect that any repellent or combination of repellents will deter all individuals.

When considering the use of repellents to deter native birds from eating pest control baits, equally important to intra-specific variability in response to repellents is inter-specific variability. This is because it would be desirable to deter a wide range of non-target bird species from eating baits, so the repellent would need to effective for all of these species. Differences in the methodologies used for sparrows and native species preclude making any definitive conclusions about variations in response to repellents between sparrows and native birds. However, where the same methods were used for evaluating repellents (e.g. robins and tomtits; Chapter 6), there were differences in the preparedness of individuals of each species to interact with baits: tomtits were much less prepared to sample baits than robins. The results of all of my experiments were, however, consistent with regard to the efficacy of the repellents. Sparrows, robins and tomtits all strongly avoided the blue colour + 2% Avex combination, as did sparrows and robins presented with the 2% d-pulegone + 2% Avex combination (tomtits were not tested with this combination). Anthraquinone has been recognised as an avian feeding repellent since the 1950s (Neff and Meanley, 1957) and I have found research describing highly effective anthraquinone repellency for at least 19 bird species with various feeding strategies and ecologies (e.g. Avery *et al*, 1997; 1998; Ballinger, 1999; 2001). Only four studies have been described where anthraquinone did not - effectively deter the target avian. In each of these studies, the method of application of anthraquinone was suggested to have reduced its efficacy, rather than the repellent being ineffective (e.g. Avery *et al*, 2000).

The fact that anthraquinone appears to elicit strong avoidance in a wide range of bird species (Avery *et al*, 1997; 1998) is encouraging for the development of repellents to be used in pest control baits. The effective combinations of repellents in my thesis all used anthraquinone (2% Avex) as the secondary repellent, so it possible that many bird species I did not test will also avoid these combinations. Further research is now required, using birds with different styles of feeding behaviour from the species I studied. Native parrots (e.g. kaka, kea) and rails (e.g. weka) have previously been tested with various bait compositions and have been found to be difficult to deter from feeding (e.g. Hartley *et al*, 2000; Hickling, 1997). It will be important to determine whether blue colour + 2% Avex, or 2% d-pulegone + 2% Avex will reduce food consumption by these species. Each of these species is known to feed on baits

(Spurr, 2000) and is adept at manipulating food items in their feet and bills (Hartley, 1999; Heather and Robertson, 1996).

Suitability of test methods used

The experimental methods I used in this thesis varied for each of the three bird species tested. The methods were designed to gain the maximum quantity and quality of data on repellent efficacy, from a limited number of individual birds or flocks. Like many other repellent studies, my methods were designed primarily to determine whether repellents had an effect on feeding behaviour (food consumption), rather than to specifically identify the mechanisms by which any effect occurred. For sparrows, experiments tested the feeding behaviour of flocks of birds rather than individuals. With native birds, experiments using individual birds were designed to mimic the situations in which birds may find baits in the wild. These differences must be considered in interpreting the outcomes of my research.

House sparrow flocks or populations were offered repellent-treated food (Chapters 2 and 4), and the feeding behaviour of individual sparrows was not recorded. I decided it was valid to test sparrows with repellents in a group situation, because the feeding choices of flocking birds are usually consistent with their flock mates (Reidinger and Mason, 1983; Ward and Zahavi, 1973). Given the high level of avoidance for some of the repellent combinations (e.g. blue colour + 2% Avex), it appears that most sparrows in my study responded in a similar manner to effective repellents. However, it is possible that a few sparrows were never deterred from eating repellent-treated wheat (there was always at least a small amount of repellent wheat removed), despite the seeming strong avoidance by most birds. Additionally, the flock composition may have varied from day to day, potentially masking any temporal changes in wheat consumption in response to aversive repellent treatments. Little is known about day-to-day changes in sparrow flock composition in New Zealand, so I cannot comment on whether this may have affected the day-to-day repellent wheat consumption I recorded.

In contrast to sparrows, the feeding behaviour of individual robins (Chapters 3, 6 and 5) and tomtits (Chapter 6) towards repellents was recorded, because these birds usually feed singly (Heather and Robertson, 1996). This enabled me to determine, for

robins, that some individuals pecked at and removed more repellent-treated bait than others. For example, male robins were more prepared to peck at 2% d-pulegone + 2% Avex-treated dough than females (Chapter 3) and some juvenile robins pecked at more blue colour + 2% Avex repellent baits than adults (Chapter 5). Measuring the feeding behaviour of individual birds was time-consuming compared to testing the sparrow populations, but provided data demonstrating the specific effects of each repellent on different individuals. These data highlighted that the repellents did not have exactly the same level of effect for all individuals and this should be considered when pest control baits containing bird repellents are used: some birds may still eat baits and die.

  The availability of alternative food sources may be an important factor when comparing tests of repellent effects between species, populations and individuals. In Chapter 5, I used individual robins to compare the effect of choice and no-choice bait presentation methods on repellent efficacy. Because I was using free-ranging birds, they always had alternative (natural) food sources available to then during my experiments, even when one bait type only was presented. However, the bait material I presented the repellents on (a lard-based dough), proved to be highly palatable to robins (Chapter 3) and they readily ate it if it did not contain repellent. I found that some robins did peck more frequently at repellent-treated baits in the no-choice test situation, but that the repellent combination still prevented almost all bait ingestion. Animals are considered to be less sensitive to the effects of repellents in no-choice tests than in choice tests (Clark, 1997) and repellents that are effective in the choice situation may not work in no-choice tests. The fact that the repellent combinations I tested were effective with wild sparrow populations (where some birds may have had limited choice) and wild robins (in choice and no-choice tests) indicates that the combinations were highly aversive. The no-choice test I used is similar to the conditions in which robins would find baits during a control operation (i.e. a single type of bait lying on the forest floor), and therefore, the results of my experiment would most likely be relevant to the field situation. However, a number of differences exist between the experimental and field conditions (e.g. birds were trained to approach, baits were cut into small pieces to encourage feeding), so confirmation of these findings will be required during normal pest control operations.

Comparison of sparrow and native bird experiments

The repellent combinations that most significantly suppressed sparrow feeding in this thesis (2% d-pulegone + 2% Avex, Chapter 2; blue colour + 2% Avex, Chapter 4) also proved to be repellent to robins (Chapter 3 and 5) and tomtits (Chapter 6). This indicated that the sparrow experiments conducted were an appropriate predictor of repellent effects on robins and tomtits, at least for the repellents and concentrations tested. This result may have been expected, given that anthraquinone has previously been proven to be highly effective for a wide range of avian species (Ballinger, 1999; 2001). Additionally, sparrows are extremely tolerant of some repellents, requiring high concentrations to effectively repel them (Moran, 2001). This makes sparrows a robust and conservative test of repellent efficacy, because repellents that deter sparrows from feeding are likely to deter most other species as well. The sparrow experiments were easy and cost-effective to conduct, with no shortage of sparrows against which to rapidly screen many repellents in New Zealand conditions.

  In this thesis I did not determine the full extent of the relationship between the sparrow experiments and robin experiments over a wide range of repellents and concentrations. For example, some of the repellents that were of very low efficacy for sparrows (e.g. lime, neem oil; Chapter 2) may have effectively repelled robins had I tested them. Many robins may also have been repelled by much lower concentrations of Avex than is required to repel sparrows, but I only tested repellent concentrations that were effective for sparrows. If studies were conducted with sparrows to determine the minimum effective concentration of Avex + blue colour that was effective, the same concentration may no longer repel robins, if robins were more tolerant to the effects of Avex than sparrows. I recommend that further research is conducted to determine the aversion thresholds created by each experimental situation, such that when a repellent is proven to deter sparrows one can be extremely confident it will also deter robins or other native species. This would improve the utility of the sparrow experiments for future work related to native bird repellency.

Will repellents prevent native bird poisoning during pest control operations?

All of the experiments I conducted with native birds in this thesis were designed to compare the efficacy of repellent-treated baits against 'standard' baits (containing

green colour and cinnamon oil) currently used for pest control. In Chapter 3, robins readily pecked at and consumed fragments of standard green-cinnamon cereal, carrot and dough baits. This observation was consistent with the finding that robins are occasionally poisoned during aerial control operations using green, cinnamon-flavoured cereal or carrot toxic baits (Powlesland *et al*, 1999; Spurr, 2000). While it is unknown if green-dyed and cinnamon-flavoured baits do help protect some birds from poisoning, it is clear that robins, and other bird species, will sometimes consume these baits. This is an important practical finding from my research, and I must conclude that green-cinnamon baits should not be considered bird-safe.

In comparison to standard baits, 2% d-pulegone + 2% Avex (Chapter 3) and blue colour + 2% Avex (Chapters 5 and 6) significantly reduced bait sampling. Robins made very few pecks at either repellent combination and avoided the baits more strongly over time. The changes in patterns of pecking and bait removal suggest that both primary and secondary repellency were deterring bait feeding. I observed subtle differences in the preparedness of different individuals to test repellent-treated bait. A small proportion of robins, particularly juveniles, were more responsive to all baits than other birds, and these birds may be at risk of poisoning despite the use of repellents in baits. I also observed that pecking responses towards baits were greater in the winter than the summer, but the repellent remained an effective feeding deterrent. In comparison to standard baits, both repellent treatments are likely to reduce feeding on bait by robins under a range of conditions, and this may translate to fewer poisonings during pest control operations.

When comparing the feeding behaviour of robins and tomtits towards baits treated with blue colour + 2% Avex (Chapter 6), important differences in feeding behaviour were observed. In contrast to robins, tomtits never pecked at any bait they were presented with and spent much less time foraging from the ground. Tomtits have not been observed eating baits previously, but systematic studies to record bait ingestion by tomtits during pest control operations have not been attempted. My results suggest that tomtits are much less prepared to sample baits, at least in the experimental circumstances presented, than robins. Further research will be required to clarify whether deaths of tomtits during pest control operations (Powlesland *et al*, 2000) are caused by primary (bait consumption) or secondary (consumption of other toxic material, such as invertebrates that have fed on baits) poisoning, and therefore,

whether bird repellent baits would afford tomtits any protection. Similar studies will be required for other species that may also be susceptible to secondary poisoning.

A key step remaining in the application of repellents to pest control baits will be the acceptance of these baits by the target pests. My thesis did not address the issue of repellent acceptance by possums or rodents, although studies conducted prior to this thesis showed that pests readily ate baits treated with each of the repellents tested here (Day *et al*, 2000). The ability of baits (treated with the combinations that are effective bird repellents) to cause high levels of pest mortality during control operations is essential, and should now be clarified under the range of conditions experienced in the field. If these studies confirm that high levels of pest mortality can be obtained using bird repellent baits, then moves should be made to routinely incorporate repellents into future baits.

In their current form, either of the two main repellent combinations I tested (2% d-pulegone + 2% Avex or blue colour + 2% Avex) may help to protect some native birds from poisoning. These combinations represent a major potential advance in technology for preventing non-target deaths and all efforts should be made to see this technology implemented by the pest control industry. Further research will be required to determine the variability in repellent effects on other avian species, but given the widespread rejection of anthraquinone-treated foods by birds (e.g. Avery *et al*, 1997; 1998), the prospects of repelling other native species appear good. Ultimately, the efficacy of repellent-treated baits will need to be tested and compared to standard baits in a range of field conditions, using different bait types (Day *et al*, 2000). Repellents are unlikely to ever prevent all birds from dying during control operations, but have the potential to significantly reduce non-target avian impact.

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