The effect of Targeted Acoustic Startle Technology on the foraging success of individual harbor seals

By

Kathleen Anne McKeegan

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ADVISORY COMMITTEE

Dr. Alejandro Acevedo-Gutiérrez, Chair

Dr. Matthew Zinkgraf

Dr. Austen Thomas

GRADUATE SCHOOL

David L. Patrick, Dean

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Abstract

Rebounding pinniped populations have led to conflicts with fisheries over commercially important prey species. Acoustic deterrent devices (ADDs) are used to aid the recovery of depleted fish stocks by mitigating pinniped predation. However, most ADDs use painful sound signals, which can lead to hearing loss and habituation. Alternatively, a new ADD called Targeted Acoustic Startle Technology (TAST) decreases pinniped predation with no evidence of harm or habituation, but effects on the foraging success of individual pinnipeds is unknown. In the Salish Sea, harbor seal (*Phoca vitulina*) populations have rebounded since the early 1970's and are suspected of impeding the recovery of Pacific salmon (*Oncorhynchus* spp.). In fall 2020, TAST was deployed to deter harbor seals that reliably aggregate in the mouth of Whatcom Creek in Bellingham, WA, from preying on fall runs of hatchery chum (*O. keta*) and Chinook (*O. tshawytscha*) salmon. Field observations were conducted between 2019-2021 to assess the short-term (2020 fall salmon run only) and long-term (2019-2021 salmon runs) effectiveness of TAST on mitigating harbor seal predation. Analyses showed that TAST significantly decreased the duration that individuals remained at the creek but had variable effects on the foraging success of individuals in 2020. Generalized Linear Models showed no lingering effect of TAST on the presence or foraging success of seals the following year. I conclude that TAST may be an effective management tool in the short-term, but individual variability must be accounted for when managing predation by pinnipeds on depleted fishery species.

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Table of Contents

List of Figures

List of Tables

List of Supplementary Figures and Tables

Introduction

Background: Management of Pinniped Predation

Predation by pinnipeds on commercially important prey has been a source of conflict for centuries (Bowen & Lidgard, 2013; Hansson, Bergström, et al., 2018; Morissette et al., 2012; Tixier et al., 2021; Trites et al., 1997). Pinnipeds (seals, sea lions, fur seals, and the walrus), compete with humans over shared resources by consuming fish and shellfish of commercial interest (Hansson, Bergström, et al., 2018; Morissette et al., 2012; Tixier et al., 2021). Pinnipeds forage around aquaculture pens, near fish ladders, and prey directly off of fishery catches, which can cause gear damage, reduce overall catch for fishers, and result in possible harm to pinnipeds via by-catch or lethal retaliation (Scordino, 2010; Tixier et al., 2021). Furthermore, many key coastal fisheries overlap spatially with pinniped haul-out sites and feeding areas, increasing the likelihood of fishery-seal competition (Hansson, Bergström, et al., 2018). While scientists debate how much direct competition actually exists between fisheries and pinnipeds (Hansson, Bergström, et al., 2018; Hansson, Kautsky, et al., 2018; Trites et al., 1997; Walters et al., 2020), the perceived competition has led to frustration for fishers and a focus on managing pinniped predation (Harlan et al., 2009; Morissette et al., 2012; Oliveira et al., 2020; Yurk & Trites, 2000).

This conflict between fishers and pinnipeds is exacerbated when the fish stocks in question are depleted (Cook et al., 2015; Morissette et al., 2012). Globally, fish biomass has declined significantly over the past century, with most of the decline occurring in the last 40 years (Christensen et al., 2014; Worm et al., 2006). This decline is driven by several factors including overfishing, habitat degradation, and climate change (Christensen et al., 2014; Jusufovski et al., 2019; Myers et al., 1996; Worm et al., 2006). Overfishing is defined as human take beyond the maximum sustainable yield (MSY) of a stock (Worm et al., 2006). Exceeding regulated MSY may result in the decline of stock populations, the subsequent closure of fisheries, and detrimental economic impacts (Richerson et al., 2018; Worm et al., 2006, 2009). For example, the 2017 closure of the Pacific salmon (*Oncorhynchus* spp.) troll fishery in southern Oregon and northern California resulted in an estimated loss of $5.8-8.9 million in income, $12.8-19.6 million in sales, and 200 to 300 jobs (Richerson et al., 2018). Closures seek to aid the recovery of a targeted fish stock by decreasing fishing mortality. However, in many cases, reduced fishing mortality or fishing below MSY does not prevent fishery collapse, suggesting that either MSY is miscalculated or natural mortality, such as that caused by pinniped predation, is higher than predicted (Cook et al., 2015; Worm et al., 2009).

At the same time fisheries are collapsing or closing, many pinniped populations are rebounding thanks to conservation efforts and federal regulations (Magera et al., 2013). In the United States, the passage of the Marine Mammal Protection Act (MMPA) of 1972 made it a federal offense to "harass, hunt, capture, or kill" a marine mammal, allowing pinnipeds to recover (Magera et al., 2013; Marine Mammal Commission, 2007). Subsequently, many pinniped populations significantly increased in size, despite severe historical declines from commercial harvesting or state-sponsored bounty programs (Jeffries et al., 2003; Magera et al., 2013; Olsen et al., 2018). For example, harbor seals (*Phoca vitulina*) along the coast of Washington and Oregon experienced substantial population suppression to below 10% of their historical level prior to regulation, and have since recovered to above 90% of their historical levels (Magera et al., 2013). While the recovery of previously depleted pinnipeds may be seen as a conservation success, rebounding populations have increased predation pressures on commercially important fish stocks, leading many fishers to blame pinnipeds for their economic losses (Cook et al., 2015; Morissette et al., 2012; Oliveira et al., 2020; Roman et al., 2015; Schakner et al., 2019).

In response, management efforts are being implemented to mitigate pinniped predation on depleted fish stocks (Bowen & Lidgard, 2013; Götz & Janik, 2016; Götz & Janik, 2013; Scordino, 2010). Common management methods include: physical and electric barriers (Forrest et al., 2009; Harlan et al., 2009); acoustic deterrents (Götz & Janik, 2013; Graham et al., 2009; Jacobs & Terhune, 2002; Kastelein et al., 2017; Mikkelsen et al., 2017); pyrotechnics and projectiles (Brown et al., 2009); capturing or killing select individuals (National Marine Fisheries Service (NMFS), 1999; Scordino, 2010); and limiting predator population growth (Bowen & Lidgard, 2013; Graham et al., 2011; Nelson et al., 2020; Scordino, 2010). These methods have been applied in many different systems of concern and have had varying degrees of success (Brown et al., 2009; NMFS, 1997; Scordino, 2010). However, most management methods assume that all pinnipeds in a population are equally likely to impact the prey species despite known intraspecific variation among pinnipeds, whose diets vary across sex, location, season, and individual (Bowen & Lidgard, 2013; Lance et al., 2012; Orr et al., 2004; Schwarz et al., 2018). Many conflict situations between pinnipeds and fisheries involve specific individuals that repeatedly return and forage in locations of concern (e.g. around fish ladders or aquaculture pens) (Keefer et al., 2012; Middlemas et al., 2006; NMFS, 1999; Scordino, 2010; Wright et al., 2010). General management of pinnipeds may not be successful without addressing these ‘problem’ individuals (NMFS, 1999; Scordino, 2010). To be effective, management methods should consider individual variability of foraging success, behavior, and diet (Bowen & Lidgard, 2013; Freeman et al., 2022; NMFS, 1999; Schakner et al., 2017; Scordino, 2010).

While there are economic and ecological costs to any management method, lethal management of pinnipeds is particularly controversial (Bearzi et al., 2004; Bowen & Lidgard, 2013; Jackman et al., 2018; Morissette et al., 2012; Treves & Karanth, 2003). Lethal management often refers to predator population control though culling, the reduction of a wild population of animals through selective killing in order to increase a prey population (Morissette et al., 2012; Olsen et al., 2018; Scordino, 2010). Fueled by the pinniped-fishery conflict, several culling campaigns were deployed globally to control pinniped populations levels in the 18th and 19th centuries (Morissette et al., 2012; Newby, 1973; Olsen et al., 2018). For example, 26,000 harbor seals and 10,000 gray seals (*Halichoerus grypus*) were bountied and killed in Denmark between 1890 and 1970 to reduce their predation on salmon and their destruction of fishing gear (Olsen et al., 2018). Culling campaigns require intense and frequent population reductions to see any significant increase in prey abundance, and there is little evidence that large-scale culling to increase prey abundance is feasible or will be effective (Bowen & Lidgard, 2013; Butterworth, 1992; Morissette et al., 2012; Olsen et al., 2018).

Large-scale culling campaigns to reduce predator population size have become less common since the passage of the MMPA and similar regulations worldwide. In the United States, permits must be issued in accordance with guidelines specified by the Marine Mammal Commission to lethally remove a pinniped. Permits typically allow only targeted individual pinnipeds to be removed based on repeated appearances at the site of concern (Marine Mammal Commission, 2007). These targeted predators eligible for lethal removal are considered 'rogue' or 'problem' individuals, meaning they repeatedly return to the site of concern and consume a disproportionate amount of prey relative to others in the same population (Graham et al., 2011; Keefer et al., 2012; Wright et al., 2010).

The scientific evidence to justify culling of rogue individuals is uncertain, and it can be difficult to assess the success of this management method (Bowen & Lidgard, 2013; Graham et al., 2011; Morissette et al., 2012). For example, at Bonneville Dam in the Pacific Northwest, a growing aggregation of California sea lions (*Zalophus californianus*) and Steller sea lions (*Eumetopias jubatus*) prey on threatened Pacific salmon stocks, with many individuals repeatedly returning to the dam year after year (Keefer et al., 2012; Scordino, 2010; Wright et al., 2010). In response, managers lethally removed 40 high-impact repeat-visit California sea lions between 2008-2010; however, this management action was highly contentious and the effects of the removal are not well understood (Keefer et al., 2012). The contention is derived from the fact that the public has placed more value on marine mammals in recent years, making it difficult to obtain public support for the culling of pinnipeds or other 'charismatic megafauna' (Bowen & Lidgard, 2013; Jackman et al., 2018). Further, many pinniped populations are still recovering or have only recently recovered after years of over-exploitation and human disturbance (Bowen & Lidgard, 2013). Consequently, non-lethal methods may be preferred for the management of pinniped predation (Jackman et al., 2018).

The most widely used non-lethal management tools are Acoustic Deterrent Devices (ADDs), which are generally considered effective and benign ways of mitigating pinniped predation (Kastelein et al., 2017; Schakner & Blumstein, 2013; Todd et al., 2019). ADDs utilize loud sound signals to cause pain in the target species and subsequently deter predators from foraging in a specific area (Kastelein et al., 2017; Schakner & Blumstein, 2013). These pain-inducing ADDs, often referred to as 'seal scarers' or 'seal bombs', not only contribute to large-scale noise pollution, but also cause hearing damage or habitat displacement for both target and non-target species (Götz & Janik, 2013; Schaffeld et al., 2020; Todd et al., 2019). For example, a signal from a typical commercial ‘seal scarer’ can induce severe hearing impairment in harbor porpoises (*Phocoena phocoena*) and other species sensitive to noise pollution (Götz & Janik, 2013; Schaffeld et al., 2020). Yet, pain-inducing ADDs that are not sufficiently aversive, while effective in the short-term, are generally unsuccessful in the long-term due to habituation (Scordino, 2010). Over time, the sound signal becomes a neutral stimulus and the animal can learn to associate it with prey, a phenomenon termed the ‘dinner bell effect’ (Schakner & Blumstein, 2013). To be effective, ADDs must specifically target the intended predator and maintain sufficient adverse effects over time (Götz & Janik, 2015; Götz & Janik, 2013; Schakner & Blumstein, 2013).

Non-lethal deterrents that utilize behavioral biology are more likely to have long-term success in mitigating predation (Götz & Janik, 2015; Kastelein et al., 2017; Schakner & Blumstein, 2013; Todd et al., 2019). A new ADD design, known as Targeted Acoustic Startle Technology (TAST), produces reliable, long-lasting avoidance behaviors in harbor seals and grey seals (Götz & Janik, 2011, 2016). TAST was developed by GenusWave, a company founded by biologists from the Sea Mammal Research Unit at the University of St. Andrews, and was designed to target seals preying on salmon without harming other species of concern (Götz & Janik, 2015, 2016). TAST uses short onset-time sound stimuli to trigger the acoustic startle reflex, a startle response that is associated with the ‘flight behavior’ in seals (Götz & Janik, 2016; Koch, 1999; Yeomans et al., 2002). The startle response is a simple reflex arc characterized by a fast motor response, similar to flinching, and can be triggered by sudden and intense acoustic stimuli (Götz & Janik, 2011; Koch, 1999; Yeomans et al., 2002). This acoustic startle reflex is conserved across many mammalian taxa and is believed to help protect an organism from life-threatening impacts or predatory attacks (Koch, 1999; Yeomans et al., 2002). Götz and Janik

(2011) found that the repeated triggering of the startle reflex in seals led to sensitization, rather than habituation. In other words, the seals developed a fear-conditioned response and a subsequent avoidance behavior to the signal, impacting their motivation to access known prey items (Götz & Janik, 2011). This suggests that TAST could have a long-lasting effect on pinniped foraging behavior beyond the short-term muscular startle response.

To target pinnipeds specifically, the sound signals emitted by TAST are played within a lower frequency range than most commercial ADDs (Götz & Janik, 2013). Due to differences in hearing sensitives, the 'perceived loudness' of a sound signal varies across species (Götz & Janik, 2013). For example, odontocetes (toothed whales) are more sensitive than pinnipeds to sound frequencies between 4 and 40 kHz, the frequency band that most typical ADDs utilize (Götz & Janik, 2013). In other words, odontocetes will be able to detect sound signals in this frequency band at quieter levels than pinnipeds, resulting in a greater impact on these non-target species. On the other hand, pinnipeds are more sensitive within the 1 to 2 kHz frequency band than odontocetes or bony fishes, meaning a sound signal in this frequency band can be played at lower, less painful decibel levels and still affect the targeted predator (Götz & Janik, 2013). By exploiting inter-species differences in hearing sensitivities, TAST can theoretically deter pinnipeds without affecting non-target species and without causing pinniped hearing damage (Götz & Janik, 2015).

In practice, TAST decreases predation success of pinnipeds with no evidence of habituation or adverse impacts to non-target species (Götz & Janik, 2015, 2016). TAST tested on Atlantic salmon (*Salmo salar*) farms in Scotland reduced seal predation by 91-93% and significantly decreased the number of salmon lost compared to control sites (Götz & Janik, 2016). Furthermore, sound exposure decreased the number of seals within 250 m of the device but did not alter harbor porpoise behavior or distribution (Götz & Janik, 2015). However, some individual harbor seals tolerated the sound within 250 m and it is possible that the majority of fish mortality was caused by only a few individual seals (Götz & Janik, 2016; Trites & Spitz, 2016). These data suggest that although TAST can target one species, it may not deter all individuals within that species (Götz & Janik, 2015, 2016; Trites & Spitz, 2016). Furthermore, the study was conducted at a location where alternative TAST-free salmon farms were readily available, so the motivation to remain and forage near the device was low (Trites & Spitz, 2016).

In the summer of 2020, TAST was deployed at the Ballard (Hiram M. Chittenden) Locks in Seattle, Washington, to deter harbor seals and Steller sea lions preying on salmon near the fish ladder (Bogaard, 2021; Williams, Ashe, Bogaard, et al., 2021). During the study, pinniped presence declined by around 20-25%, and statistical analysis showed a 49.3% reduction in predation rate when TAST was operating (Williams, Ashe, Bogaard, et al., 2021). Furthermore, TAST redistributed harbor seals away from the fish ladder and increased overall fish passage through the ladder, although some seals remained within 10 m of the device (Bogaard, 2021; Williams, Ashe, Bogaard, et al., 2021). While these data from Scotland and Seattle show encouraging results, no study has yet assessed the effects of TAST on the foraging success of individual pinnipeds, either in the short-term or the long-term, and no study has yet assessed the lingering effects of TAST a year or more after the device was deployed.

Case Study: Harbor Seals in the Salish Sea

In the Pacific Northwest, rebounding harbor seal populations have renewed conflicts between seals and fishers. Pacific harbor seals, found throughout the west coast of North America, are the most abundant pinniped in the Salish Sea, the inland waters around Washington, USA, and British Columbia, Canada (Jefferson et al., 2021; NMFS, 1997). As opportunistic hunters, they prey on various species of commercial interest, including Pacific salmon, a taxon of great ecological, cultural, and conservation concern (Adams et al., 2016; Butler et al., 2015; Cederholm et al., 2000; Chasco et al., 2017). Due to their perceived impact on commercially important fisheries, an estimated 17,000 harbor seals were lethally removed from Washington state waters as a part of a state-sponsored bounty-hunting program between 1943-1960 (Newby, 1973). After the passage of the MMPA, harbor seal populations increased 7 to 10-fold in a few decades (Jeffries et al., 2003; Magera et al., 2013; NMFS, 1997). Harbor seal populations in Washington and Oregon are currently at their optimal sustainable population (OSP) levels and several stocks continue to increase in size despite anthropogenic threats, such as bioaccumulation of toxins, illegal killings, and overfishing (Baird, 2001; Brown et al., 2005; Jefferson et al., 2021; Jeffries et al., 2003; Scordino, 2010). Specifically, there are an estimated 13,600 harbor seals throughout inland Washington waters, with the Hood Canal and Southern Puget Sound stocks steadily increasing since 1999 (Jefferson et al., 2021). While the recovery of the harbor seal population can be seen as a conservation success, potential trophic level impacts have led scientists and fisheries managers to question the protected status of harbor seal populations in the Salish Sea (Nelson et al., 2020; Scordino, 2010).

As harbor seal numbers continue to climb, Pacific salmon stocks have significantly declined over the last century due to habitat loss and degradation, environmental fluctuations, and harvesting pressure (Lichatowich et al., 1999; NMFS, 1997; Nehlsen et al., 1991; Pacific Salmon Commision (PSC), 2015; Sobocinski et al., 2021). By 1991, 214 stocks of Pacific salmon were designated as high risk, moderate risk, or of special concern throughout the Pacific Northwest (Nehlsen et al., 1991). The total abundance of Chinook salmon (*O. tshawytscha*) in the Pacific Northwest has steadily decreased over the past several decades, from estimated counts of around one million in 1984 to around 500,000 in 2018 (PSC, 2015). Additionally, nearly 30% of the 1400 historical populations of Pacific salmon have gone extinct in the Pacific Northwest since European colonization (Gustafson et al., 2007), and there are current widespread declines in productivity of wild chum salmon (*O. keta*) stocks in Washington and British Columbia (Malick & Cox, 2016).

Although not responsible for the decline in Pacific salmon populations, harbor seal predation may be hindering the recovery of depleted stocks (Chasco et al., 2017; Nelson et al., 2020; Sobocinski et al., 2021; Wargo Rub et al., 2019; Wright et al., 2007). Harbor seals are opportunistic predators whose diet varies depending on what prey is seasonally and locally abundant, with individuals aggregating in rivers and estuarine environments to forage on both out-migrating and spawning salmon (Adams et al., 2016; Allegue et al., 2020; NMFS, 1997). Throughout the Salish Sea, harbor seal haul-out sites and foraging ranges overlap spatially with depressed Pacific salmon runs, creating a potential for seal predation pressure to affect depleted stocks (NMFS, 1997). Adult Pacific salmon are most vulnerable to pinniped predation during their spawning migration through estuaries and river mouths, especially when the salmon are concentrated around anthropogenic bottlenecks such as human-made fish ladders (Bigg & Fisher, 1990; NMFS, 1997; Scordino, 2010). In response, management efforts are focused on finding effective methods to mitigate harbor seal predation on returning Pacific salmon in the Salish Sea (Nelson et al., 2020; Scordino, 2010).

To be effective, the intraspecific variation in foraging technique and success of individual harbor seals should be accounted for in management tools designed to mitigate seal predation on spawning salmon (Götz & Janik, 2016; Trites & Spitz, 2016). Harbor seals in the Salish Sea exhibit significant diet differences and utilize different foraging techniques, which varies across location, sex, and body size (Bjorkland et al., 2015; Schwarz et al., 2018; Voelker et al., 2020). Further, there is global evidence that a small proportion of individual harbor seals choose to forage within rivers on salmonid species (Graham et al., 2011; Middlemas et al., 2006; Scordino, 2010; Wright et al., 2007). Some river specialists continually return to the same foraging site and are especially successful, classifying them as 'rogue' when compared to others in the same population (Freeman et al., 2022; Scordino, 2010). However, this intraspecific variation in foraging success has not yet been accounted for in the assessment of harbor seal predation management tools, such as TAST (Götz & Janik, 2016; Trites & Spitz, 2016).

In the fall of 2020, a TAST deterrent device was deployed near a salmon hatchery fish ladder at the mouth of Whatcom Creek in Bellingham, Washington, to deter harbor seals from preying on adult Pacific salmon. Prior long-term research at Whatcom Creek has identified harbor seals that reliably aggregate over multiple consecutive years during the fall adult salmon run (Farrer & Acevedo-Gutiérrez, 2010; Freeman et al., 2022). Among the individual harbor seals observed at Whatcom Creek, there is documented variability in foraging success as well as evidence of rogue individuals who are of particular management interest due to their heightened consumption of the salmon stock (Freeman et al., 2022). This provided a unique opportunity to assess the impacts of TAST on the foraging success of known individual harbor seals. TAST has been shown to successfully reduce the total number of seals foraging near the device (Bogaard, 2021; Götz & Janik, 2016; Williams, Ashe, Bogaard, et al., 2021), but this is the first study to assess if TAST successfully reduces the capture efficiency (number of fish eaten per seal) of the individuals that occur in the area.

In this study, I examined the hypothesis that the presence and foraging success of individual seals would be related to TAST status in the short-term, predicting fewer successes and less time spent foraging for each individual seal when TAST was deployed compared to control conditions. Further, I examined the hypothesis that TAST would affect presence and foraging success of individuals in the long-term, predicting fewer successes and fewer days present per individual in the year TAST was deployed (2020) and the year after TAST was deployed (2021) compared to the baseline previous year (2019). To address these hypotheses, I used observational and photographic data from 2019-2021 to identify and relate individual seals to successful foraging attempts as a function of TAST status.

Methods

Study Site

Observations were conducted at the mouth of Whatcom Creek (48°45'17.5"N, 122°28'56.7"W) in downtown Bellingham, WA (Figure 1). The mouth of the creek is relatively small and is located within a public park, allowing for easy access via trails, elevated boardwalks, and sidewalks. The study site is influenced by tide and measures approximately 215 m in length, 25-58 m in width, and covers a surface area of approximately 7,225 m^2. The creek flows northeast to southwest from Lake Whatcom to Bellingham Bay and supports small wild runs of coho salmon (*O. kisutch*) and steelhead (*O. mykiss*). Furthermore, Whatcom Creek Hatchery, located on the northwestern bank of the study site, is run by the Bellingham Technical College and maintains a population of Chinook and a significantly larger population of chum salmon (Madsen & Nightengale, 2009; Washington Department of Fish and Wildlife (WDFW), 2020). The adult chum salmon run occurs from October to December and reliably attracts a large number of harbor seals and fishers to the creek (Freeman et al., 2022). Due to low returns, the salmon fishing season was closed to anglers in the fall of 2020 and 2021.

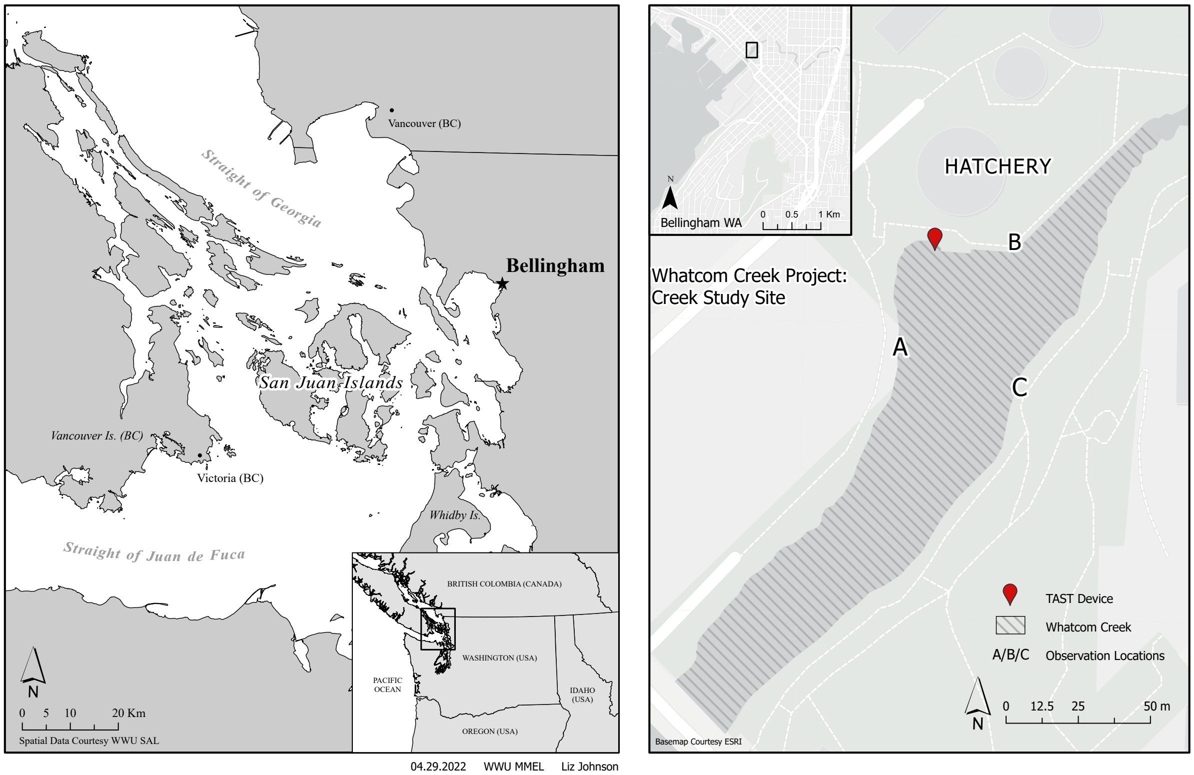

Figure 1. *Location of Whatcom Creek in the Salish Sea. The location where TAST was deployed is designated by the red teardrop. Observations were conducted at one of three locations, denoted by letters, all of which offer a clear view of the site. Location A was the location most frequently used by observers. Map courtesy of Liz Johnson.*

TAST

Between October and November of 2020, researchers from Oceans Initiative, in collaboration with the Bellingham Technical College, the Whatcom Creek Hatchery, and the Washington Department of Fish and Wildlife (WDFW), deployed a TAST device at the base of the hatchery fish ladder in Whatcom Creek (Figure 1). The TAST device, approximately half a meter in height, consists of a control unit, transducer, and a power cable that is used to hang the transducer from a fixed point and lower it into the water (Williams, Ashe, Reiss, et al., 2021). The sound signal has a peak frequency of 0.95-1.0 kHz and a pulse duration of roughly 200 ms long with sharp rise times of <5 ms (Götz & Janik, 2015, 2016). The signal is sent out at roughly 2.4 pulses per min and is played at irregular or pseudorandom intervals (Götz & Janik, 2015).

The device was first deployed at the creek on October 26th, 2020 (Williams, Ashe, Reiss, et al., 2021). The transducer was lowered using a pulley system and was attached to the railing at the base of the hatchery fish ladder. The transducer was only lowered during high tide to fully submerge the instrument to its 1.5 m minimum operating depth (Williams, Ashe, Reiss, et al., 2021). The deployment of the device followed a Controlled Exposure Experimental design (Tyack et al., 2003), cycling between a three-days-on experimental treatment condition and one-day-off control condition during the 29 days until the final deployment on November 23rd, 2020 (Williams, Ashe, Reiss, et al., 2021).

Field Observations

Harbor seals consume small prey underwater but come to the surface to control and handle larger prey items, such as adult salmon (Freeman et al., 2022; Roffe & Mate, 1984; Wright et al., 2007). Thanks to this surface-feeding behavior, we were able to observe and record harbor seal foraging successes from the banks of Whatcom Creek. Between 2019-2021, an average of 4 observations a week (SD± 1.4 days, n = 111 observations) were conducted throughout the fall adult salmon runs (October – December). Observations were made by students from the Marine Mammal Ecology Lab at Western Washington University. Following the methods laid out in Freeman (2022), 2-3 students observed the creek for two hours around slack tides, when the tide shifts from low or high tide and the water is relatively still. Observations were made from one of three locations (Figure 1), depending on weather conditions, glare, and accessibility. At regular half-hour intervals, observers recorded TAST status (on or off), weather conditions (rainy, overcast, sunny, etc.), number of seals present, number of fish caught by seals, number of fishers present, and number of fish caught by fishers.

Throughout the two-hour observation, photos were taken of the right, left, and front side of each seal's face every time they surfaced (Freeman et al., 2022). Observers used two digital Cannon EOS 60D cameras, one with a 75-300mm lens and the other with a 100-400mm lens. Photos were used to identify *a posteriori* individual seals present during an observation. Observers also recorded the time, duration, and location of all harbor seals seen at the surface of the creek. Every salmon caught by a seal was noted and additional photographs were taken of the seal that was hunting and/or eating the salmon.

Additional observations were conducted by Oceans Initiative during TAST deployment in 2020. Researchers took photos opportunistically using a DSLR camera with a telephoto lens during observations between October 26 - November 23, 2020 (Williams, Ashe, Reiss, et al., 2021). Photographs collected by Oceans Initiative were compiled and included in the *a posteriori* photo identification analysis, as described below. To account for the added sampling effort in fall 2020, photos from Oceans Initiative were only included in the short-term 2020 analysis comparing experimental conditions (TAST on) to control conditions (TAST off). Photos from

Oceans Initiative were excluded in the long-term 2019-2021 analysis to reduce the likelihood of confounding variables. All short-term analyses were run with and without data collected by Oceans Initiative to ensure results were consistent despite variations in sampling effort. Further, observation length (min) and number of cameras present per observation were included as potential factors during statistical analyses to assess if sampling effort was a major driver of variation in fall 2020.

Salmon Occurrence

Salmon return data were provided by staff of the Whatcom Creek Hatchery. Return data consisted of counts of living and dead male and female chum, Chinook, and coho salmon present in the adult holding pool. Escapements were counted opportunistically on a near daily basis between October and December for 2019, 2020, and 2021. From the daily counts, a 5-day rolling average was calculated for each salmon run season to account for the days in which salmon were not counted by the hatchery. Similar to Freeman et al. (2022), these rolling averages were used as a rough estimate for relative salmon abundance in Whatcom Creek during field observations.

Photo Identification of Individual Seals

To identify individual seals, photos taken during the observation period were selected, cropped, and compared to an existing ID catalog. The catalog is comprised of all seals that have visited Whatcom Creek since 2011 and includes high quality photos of the left, front, and right side of each seal's face (Freeman et al., 2022). Using similar methods to those described in Freeman et al. (2022), seals were identified using the unique fur patterns on their face and any other distinguishing characteristics, such as eye color or the presence of scars (Harting et al., 2004; Thompson & Wheeler, 2008). For every minute of the observation period, photos were selected of each individual seal present and for each head position (left, right, and front), while considering focus and clarity. Selected photos were cropped to include only the individual seal's head. That individual was then identified manually by matching at least three unique features to an existing ID in the catalog, and each match was confirmed by at least two independent observers.

Photos were labeled with the ID of the seal, the date of the observation, the time the photo was taken, and the side of the seal's face. If the two independent observers confirmed that an individual did not match an existing ID, a new ID was created after high-quality photos of the right, front, and left side of its face were obtained. Partial new IDs with only the left-side angle of a seal's face were included in the analysis, but partial new IDs with only a right-side or front-side were removed to ensure no seal was double-counted. A photo was discarded as 'unidentifiable' if it was poor-quality, only showed unidentifiable features (i.e., the seal's back, flippers, or belly), or if the independent observers could not find and match at least three unique features.

Presence and Duration of Individual Seals

Selected, cropped, and identified photos were used to quantify an individual seal's presence in Whatcom Creek, and subsequently their number of foraging attempts during 2019-2021. An individual seal was considered present during a field observation if at least one photo was successfully selected and identified within that two-hour period. Seal presence in the creek was considered a foraging attempt for that individual seal. Prior long-term research indicates that harbor seals are most abundant in Whatcom Creek during the fall adult chum salmon run, with significantly fewer seals, if any, present during the rest of the year (Farrer & Acevedo-Gutiérrez, 2010; Freeman et al., 2022). Additionally, harbor seals have searched, pursued, captured, and consumed adult salmon every year during the fall run since observations began in 2011 (Freeman et al., 2022). Thus, it is reasonable to consider each visit to the creek a foraging attempt for that individual, allowing us to compare foraging attempts and successes for individuals across TAST status.

To get a proxy for duration (the time that each individual seal foraged at Whatcom Creek within an observation), each minute an individual was successfully identified was tallied as a single 'surface count'. That is, every time an individual seal surfaced, a photo was taken, identified, and attributed as one 'surface count' for that individual. Surface counts were tallied on a minute increment based on when the identified photo was taken. On average, a single seal at the creek spends 21.7s (SD ± 14.9s, n = 1071 observations) at the surface, so it is reasonable to count each minute as a separate surface count. Henceforth, I refer to these surface counts as duration in minutes. Thus, by photographing and identifying individual seals at every surfacing event, I was able to unambiguously determine the relative amount of time that each individual remained at the creek and compare it to TAST status.

Foraging Success of Individual Seals

Following Freeman et al. (2022), a foraging success was defined as a successful foraging attempt in which a seal was seen actively eating a salmon at the surface. Foraging successes were recorded in the field and confirmed *a posteriori* using photographic evidence. Photos were analyzed to determine if a seal had procured an adult salmon, and that seal was then identified and credited with a foraging success for that observation.

At times, seals were associated with multiple foraging successes, meaning the same individual captured and consumed multiple salmon throughout the same observation period. Multiple foraging successes were summarized as ‘number of catches’, or number of salmon caught per seal. Associating number of catches to an individual had inherent difficulties. Harbor seals require several minutes to consume large adult salmon, and surface many times consuming the same prey item (Carter et al., 2001). Furthermore, observers frequently witnessed seals stealing from others, sharing a single prey item amongst many seals, or dropping prey before it was fully consumed. Therefore, it was not always possible to distinguish when a new adult salmon was captured by the same individual. To account for this challenge, I employed a conservative standard of 25 min to determine the number of fish caught per individual seal per observation. This standard was based on a sample of observations of surface-feeing time made between 2019-2021 at the study site (mean = 14.5 min, max = 25 min, SD ± 5.8 min, n = 17 observations). As such, a seal would only be attributed with a second catch if a salmon was seen in the seal’s mouth 25 min after that individual’s first foraging success. While this standard is conservative, it accounts for cases of sharing and stealing and allows for number of catches to serve as a proxy for number of salmon caught and consumed during an observation.

Site Fidelity of Individual Seals Across Years

Each individual seal that was identified during the 2019 - 2021 run seasons was grouped according to their across-years site fidelity. I defined site fidelity as an individual harbor seal returning over more than one year to forage on salmon at Whatcom Creek. Using data collected by the Marine Mammal Ecology Lab from 2011-2018 (Freeman et al., 2022), seals were grouped as either ‘Returners’ or ‘New’ for each year in the study. ‘Returners’ were seals that had been observed foraging at Whatcom Creek for at least one day in years prior to 2019. Seals were classified as 'New' if they were observed and identified for the first time in 2019, 2020, or 2021. An individual seal could be classified as 'New' in 2019 and then, if observed again in one or both of the following years, would subsequently be classified as a 'Returner' for 2020 and/or 2021.

Statistical Analysis of Short - Term Effects of TAST: Fall 2020

The presence, duration, and number of foraging successes for each individual harbor seal was compared across TAST on and off days in fall 2020. TAST was deployed from October 26th to November 23rd. Seal observations within this window were assessed to compare experimental treatments (TAST on) to control treatments (TAST off). To balance the dataset, I included the observation that was conducted prior to the first deployment of TAST and the observation that was conducted after the last deployment of TAST, resulting in an experimental window that spanned the peak of the salmon run season: October 25th – November 25th, 2020. Within this window, 27 days of observations were conducted, however there were three days in which two observations occurred (one conducted by the Marine Mammal Ecology Lab, the other by Oceans Initiative), resulting in 30 observational periods. Of those 30 observations, 14 were conducted when TAST was off and 16 were conducted when TAST was on.

<u>Effect on the Presence and Duration of Individual Seals</u>

All statistical analyses were conducted using R statistical software version 4.1.0 (R Core Team, 2020). To test if TAST impacted the presence and duration of individuals at Whatcom Creek, a permutational multivariate analysis of variance (PERMANOVA) was conducted on the

30 observational samples at Whatcom Creek in fall 2020. Each ID (n=98) was a part of a multivariate response matrix, with their duration as the 'abundance' of that individual per observation. PERMANOVA was performed to test the hypothesis that the centroids of each TAST status as defined in Bray-Curtis dissimilarity multivariate space were equivalent using the 'adonis' function in the 'Vegan' R package (J. Oksanen et al., 2020). Prior to the PERMANOVA, the homogeneity of multivariate dispersion across TAST status was assessed using the 'betadisper' function from the 'Vegan' package in R (J. Oksanen et al., 2020).

To visualize the difference in harbor seal community composition across observations, I performed nonmetric multidimensional scaling (NMDS), a multivariate ordination technique that can handle non-normal ecological data for community analysis (Clarke, 1993). NMDS projects the observation samples onto ordination space in two dimensions based on the rank dissimilarity using Bray-Curtis dissimilarity index. The goodness of fit for the NMDS projection was determined by evaluating the stress value, and the lowest stress value was selected after 20 runs. Environmental variables of TAST status, tide height, 5-day rolling average of salmon counts, and total number of seals observed per observational sample were fit using the 'envfit' function in the 'Vegan' package in R (Oksanen et al., 2020).

A generalized linear mixed-effect model (GLMM) with a negative binomial distribution was used to predict the duration for each individual across TAST on and TAST off observations using the 'glmer.nb' function from the 'lme4' Package in R (Bates et al., 2015). Candidate generalized linear models (GLMs) made during the model fitting process were created using the 'glm.nb' function from the 'MASS' package in R (Venables & Ripley, 2002). TAST status (on or off) was the only fixed factor included in this analysis, as it was the only predictor I was interested in assessing. The 5-day rolling average of salmon counts, tide height, seal ID (n=98)

Julian date (n=27), length of observation (min), and number of cameras (n=3) were included as potential random effects. GLMMs are robust and flexible and allow for the analysis of non-normal data as well as the analysis of random factors (Bolker et al., 2009; Zuur et al., 2009). A negative binomial distribution was selected due the data being over dispersed, which was determined using the 'check_overdispersion' function from the 'performance' package in R (Lüdecke et al., 2021). Adjusted R^2 values for the GLMMs were calculated using the 'rsq' package in R (Zhang, 2022), and model assumptions were validated by assessing residual plots. The best fit and most parsimonious model was chosen using Akaike Information Criteria (AIC) as a comparative measure of model quality. Coefficients of the final model were exponentiated to aid with interpretation and extrapolation of effect size. The variation in duration across the levels of the random effect (seal ID) was plotted using the 'plot_model' function from the 'sjPlot' package in R (Lüdecke, 2021).

I used simple chi-squared analyses to investigate if prior seal fidelity to site impacted the presence of individuals in Whatcom Creek when TAST was on. To determine the relationship between prior seal site fidelity and presence, I used two 2x4 contingency tables to compare the number of days an individual was seen to its status as either a new or returning seal. In the first table, all seals (n=98 individuals) were categorized as either 'New' or 'Returners' and were grouped into four levels of presence in 2020 based on number of days observed: 1-2 days, 3-4 days, 5-6 days, and 7+ days. The second 2x4 contingency table assessed the relationship between prior site fidelity and the proportion of days an individual was observed when TAST was on out of the total number of days observed for that individual. Proportion of days observed was divided into four levels: 0.0-0.24, 0.25-0.49, 0.5-0.74, and 0.75-1.0, with a value of 0 meaning an individual was never observed when TAST was on. Chi-squared tests were conducted for both tables as the expected values of at least 80% of the cells were ≥5 (McHugh, 2013). The standardized residuals for both Chi-squared tests were assessed to determine if presence was significantly higher (positive residual values) or significantly lower (negative residual values) than expected across seal fidelity status. Residual values greater than |1.96| were considered significant (Agresti, 2007).

Effect on the Foraging Success of Individual Seals

GLMMs with a Poisson distribution and a logarithmic link function were used to predict the overall foraging success of seals in the creek using the 'glmer' function from the 'lme4' package in R (Bates et al., 2015). Only seals that were observed when the TAST was on and off, and therefore had foraging attempts across TAST status, were included in the analysis (n=55 individuals). This allowed me to compare how foraging success under experimental conditions differed from foraging success under control conditions for each individual seal. The fixed factor predictors in the final GLMM included TAST status (on/off) and the log number of days each individual seal was observed across on or off observations. Seal ID was included as a random intercept in the final model. The number of days seals were observed was log transformed to normalize the data and improve the residuals. To ensure the added sampling effort from Oceans Initiative did not drive the observed variation in seal foraging success, the mean observation length (min) for each seal was also assessed during model fitting and was found to be an insignificant predictor of foraging success (z=0.488, p=0.63).

The best-fit and most parsimonious model was chosen using AIC as a comparative measure of model quality. Coefficients of the final model were exponentiated and used to extrapolate the effect size of TAST on foraging success. The random effects were plotted using the ‘plot_model’ function from the ‘sjPlot’ package in R (Lüdecke, 2021). Model assumptions were validated using residual plots. Overdispersion was assessed by the ‘check_overdispersion’ function from the ‘performance’ package in R (Lüdecke et al., 2021), and no overdispersion was detected in the final model (X^2= 67.27, p=0.999). Data were checked for zero-inflation using the ‘check_zeroinflation’ function from the ‘performance’ package (Lüdecke et al., 2021), and the ratio of predicted zeros (57) to observed zeros (59) was within the tolerance range.

Chi-squared analyses were used to investigate if prior site fidelity impacted the foraging success of individual seals when TAST was on. I used 2x2 and 2x4 contingency tables to compare the foraging success of an individual to its status as either a new seal or returning seal. For the 2x2 table, seals were classified as either ‘New’ or ‘Returners’ and categorized as either ‘successful’ or ‘not successful’ in 2020, with successful meaning that the individual caught and consumed at least one salmon. For the 2x4 contingency table, seals were further divided into four categories according to when their successful foraging event or events were observed: only when TAST was on (Success_On), only when TAST was off (Success_Off), both when TAST was on and off (Success_Both), or no success observed (Success_None). Chi-squared tests were conducted for both tables as the expected values of at least 80% of the cells were ≥5, and the standardized residuals were assessed, with values greater than |1.96| considered significant (Agresti, 2007; McHugh, 2013).

Statistical Analysis of Long- Term Effects of TAST: 2019, 2020, 2021

<u>Effect on Individual Seals</u>

The presence and number of foraging successes for each individual harbor seal was compared across three separate run seasons: fall 2019, 2020, and 2021. To assess if there was a relationship between exposure to TAST in 2020 and the likelihood that an individual seal would return in 2021, I used simple chi-squared analysis and a 2x2 contingency table. Individuals that were observed in 2020 were grouped into two TAST exposure levels: ‘exposed’ or ‘not exposed’. An individual present at least once during an observation when TAST was on was grouped as ‘exposed’, and individuals that were never present during a TAST-on observation were grouped as ‘not exposed’. I then determined if those individuals were present or absent in 2021. Similarly, chi-squared analysis was used to assess if prior site fidelity of seals impacted the likelihood that an individual would return to the creek in 2021. Individuals were categorized as either ‘New’ or ‘Returners’ for 2020 based on prior observations between 2011-2019. Those individuals were then determined to be either present or absent in 2021.

Spearman correlation was used to determine if the number of catches in 2020 per ID was significantly correlated to number of catches in 2021 per ID using the ‘cor.test’ function from the ‘stats’ package in R (R Core Team, 2020). Spearman correlation was selected because the distribution of the data were not normal, as determined by the ‘shapiro.test’ from the ‘stats’ package in R (R Core Team, 2020). Chi-squared analysis on a 2x2 contingency square was used to assess if TAST exposure in 2020 had a significant association with foraging success in 2021. All individuals that were present in 2021 were categorized as either exposed or not exposed to TAST in 2020. I then determined if those individuals had a recorded foraging success throughout all 2021 observations. All chi-squared tests were conducted using the ‘chisq.test’ function in R and the standardized residuals were assessed to determine significance.

Overall Effect on all Seals

Across the peak run seasons for 2019, 2020, and 2021, the total number of seals were counted per day and the total number of salmon caught was summed across all seals per observation. This allowed me to compare how TAST affected the overall number of seals present per observation and the total number of salmon consumed by all seals across years. In fall 2020, TAST was deployed during the height of the salmon run season, from October 26th – November 23rd. To assess the varying effects across years, only the height of each season was compared. For each year, only the observations within 20 days around the peak of the salmon run were included. The peak of the salmon run for each year, as determined by the highest daily count of adult salmon in the hatchery holding pond, was 11/13/2019, 11/16/2020, and 11/17/2021. Therefore, the data compared across years included observations between 11/3/2019 – 11/23/2019, 11/6/2020 – 11/26/2020, and 11/7/2021- 11/27/2021 (Figure 2). Within these windows, 9 observations were conducted in 2019, 15 observations in 2020, and 12 observations in 2021. Of the 15 observations in 2020, 8 were conducted when TAST was off, and 7 were conducted when TAST was on.

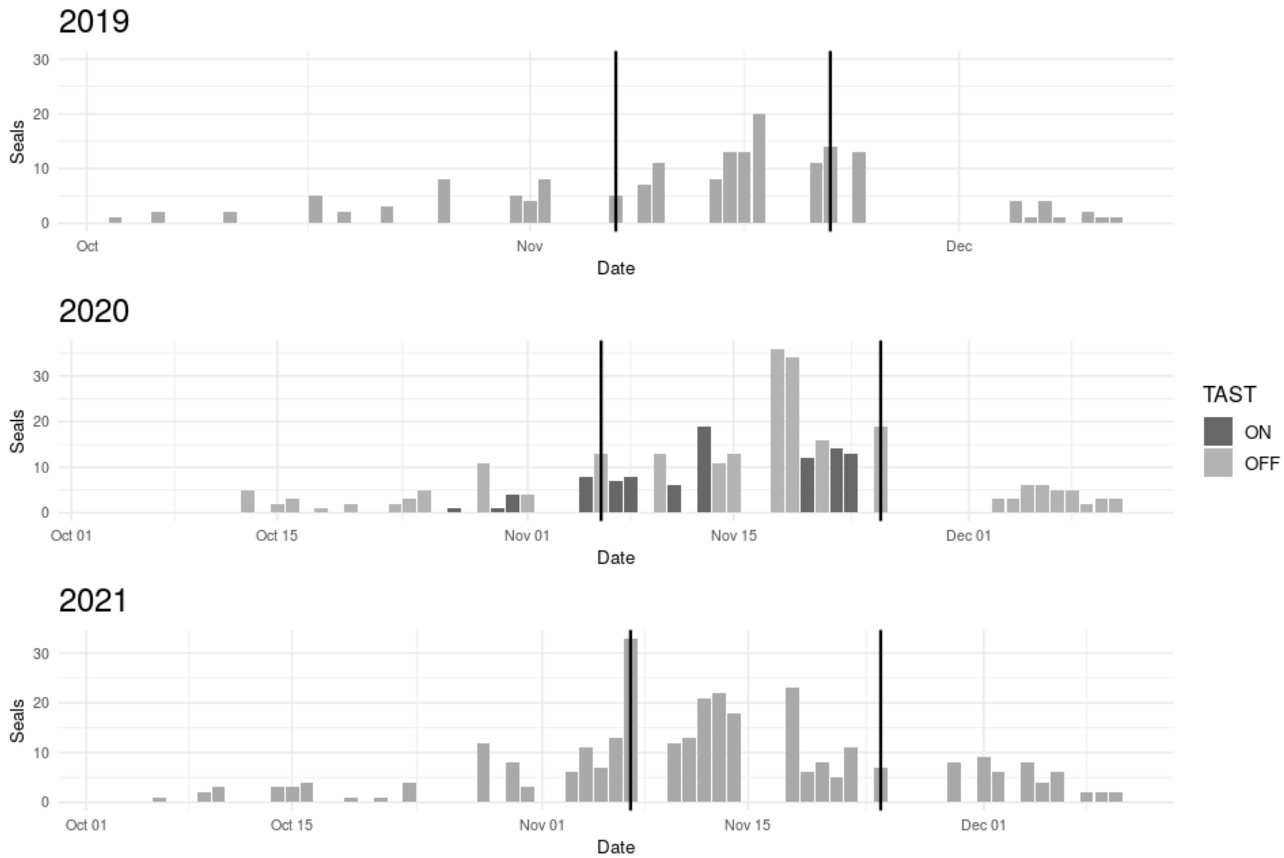

Figure 2. *Total number of seals seen per observation for 2019, 2020, and 2021. Vertical lines represent the cut offs for each experimental window per year. Experimental windows included the 20 days around the peak of the fall salmon run for each year. TAST status is denoted by fill.*

Generalized Linear Models (GLMs) with negative binomial distribution were used to statistically assess the effects of TAST across years. The first model was used to predict the total number of seals present per observation for the 2019-2021 peak run seasons. Negative binomial distribution was selected for this model to address the overdispersion in the dataset, which was determined using the 'check_overdispersion' function from the 'performance' package in R (Lüdecke et al., 2021). The second model was used to predict the total number of foraging successes (salmon caught) by all seals present per observation for the 2019-2021 peak run seasons. Similarly, a negative binomial distribution was selected to address the issue of overdispersion. For both models, TAST status (before, on, off, during) was the only fixed factor included, as it was the only predictor I was interested in assessing. Data were also assessed for zero-inflation using the 'check_zeroinflation' function from the 'performance' package (Lüdecke et al., 2021). Adjusted R^2 values for the GLM were calculated using the 'rsq' package in R (Zhang, 2022), and model assumptions were validated by assessing residual plots.

Results

Short-term Effects of TAST: Fall 2020

Effect on the Presence and Duration of Individual Seals

Within the experimental window from October 25, 2020, to November 25, 2020, TAST was on for 16 observations and off for 14 observations. Across the 30 observations, 12,254 photos were selected and 11,871 of those photos were successfully identified (96.9%), resulting in a total of 98 unique harbor seals identified at Whatcom Creek. Approximately 66% of the 98 individuals were seen for multiple days throughout the window and 33% were only seen once during the experimental window. Overall, 56% of individuals were observed both when the

TAST was on and off, with 32% only present when TAST was off. At least one California sea lion (*Zalophus californianus*) was observed 22 times across 3 observations, almost entirely when TAST was on.

Observations that were conducted by the Marine Mammal Ecology Lab prior to the first deployment of TAST identified 18 individual seals present in Whatcom Creek across 12 observations in October 2020. Of those 18 individuals, all but one (ID 0017) returned at some point during the TAST experimental window and 15 experienced a TAST exposure, meaning they were identified as present during a TAST-on observation. Of the 98 individuals observed during the experimental window, 31 seals were never identified as present in the creek when TAST was on, meaning, to the best of our knowledge, those individuals were never exposed to the device (Figure 3). The remaining 67 individuals were observed foraging in Whatcom Creek during at least one observation period in which TAST was deployed and on (Figure 3). Of those 67 individuals, 10 were not observed again at Whatcom Creek after their initial exposure to TAST (Figure 3). Most individuals (58% of the 98 seals identified, 85% of the 67 exposed seals) were present in the creek on at least one separate observation day after their first exposure to TAST (Figure 4). Of those 57 individuals that returned, 12 of them were only observed foraging on subsequent days when TAST was off (Figure 3, 4).

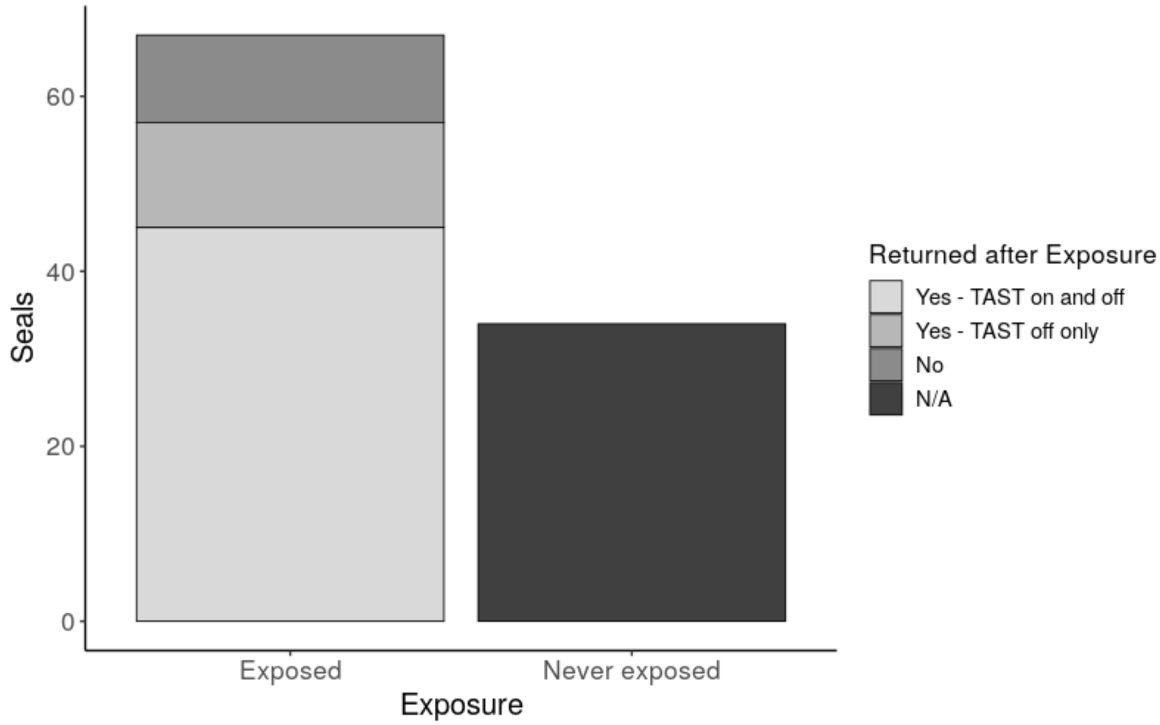

Figure 3. *Bar plot showing the number of individual harbor seals in 2020 that were present in Whatcom Creek during TAST deployment ('Exposed') compared to those that were never observed during TAST deployment ('Never Exposed'). Exposed individuals are further divided based on their presence in the creek after initial exposure: those that returned in subsequent days when TAST was on ('Yes – TAST on and off'), those that returned in subsequent days but only when TAST was off ('Yes – TAST off only'), and those that did not return after initial exposure to TAST ('No').*

Of the 98 individuals identified in 2020, 46% experienced repeated exposures to TAST, meaning they were observed on at least two separate TAST-on observation days. The overall number of days that these individuals returned to Whatcom Creek varied greatly (mean=6.3 days, SD ± 4.9 days, n=45; Figure 4). Specifically, four individuals were only present for two observations, both with TAST on, and then were not recorded foraging at the creek for the remainder of fall 2020 (IDs 0101, 0178, 0186, and 0201). On the other hand, some individuals returned regularly to the creek, both when TAST was on and off. For example, ID 0173 was present foraging at the creek on 19 separate occasions after its first TAST exposure, 12 days of which were when TAST was on. Of the 45 individuals that returned when TAST was on, over half (55%) returned for three or more separate TAST-on observation periods, with 3 individuals (IDs 0121, 0172, 0173) returning for 10 or more TAST-on observations (Figure 4).

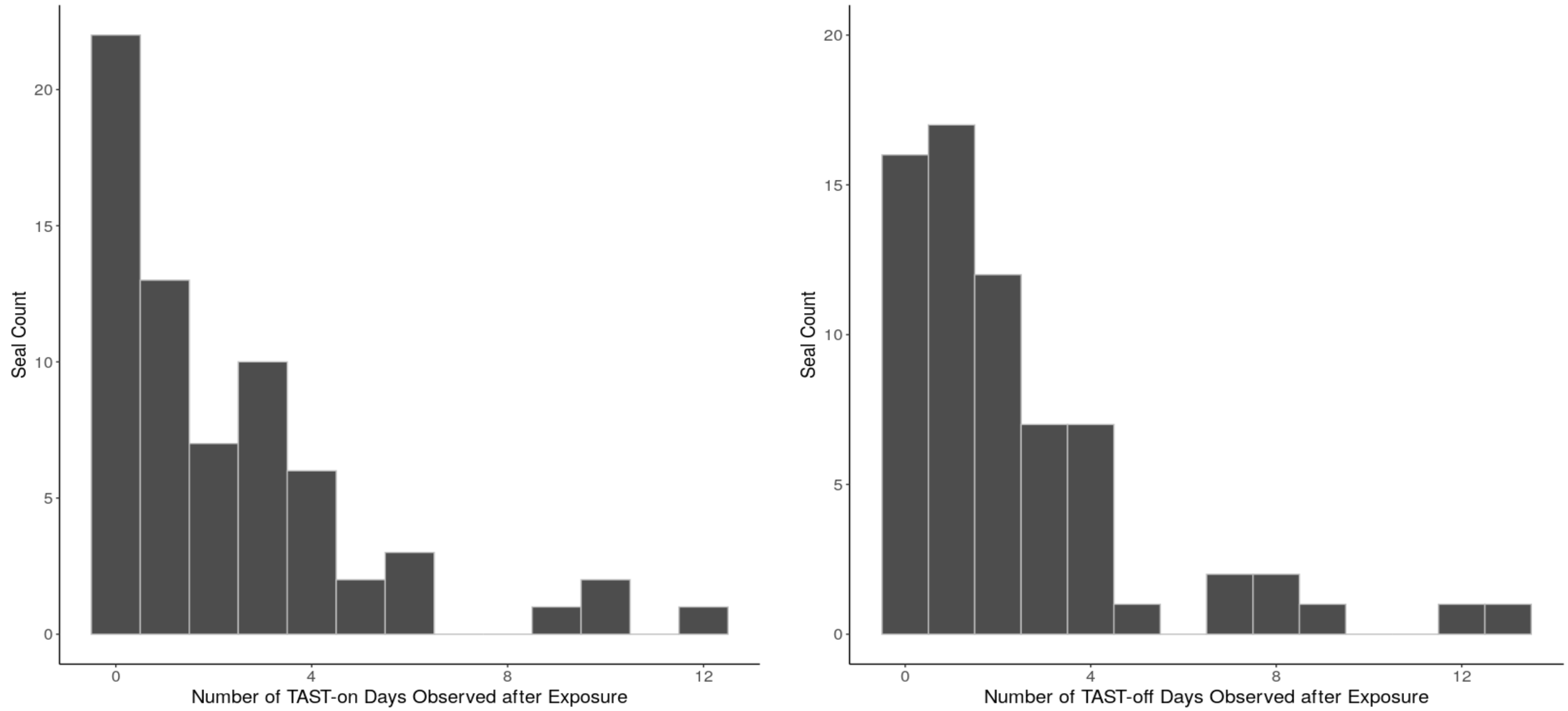

Figure 4. *Histograms showing the number of TAST-on or TAST-off days exposed seals (n=67) returned to Whatcom Creek in fall 2020 after initial TAST exposure.*

The duration (min) that individuals remained foraging in Whatcom Creek varied greatly for each individual harbor seal. On average, individual seals spent 34.5% less time in Whatcom Creek during TAST-on observations compared to TAST-off observations (Figure 5). ID 0173 was observed most frequently, with an average duration of 33 min across 22 observation days (Figure 5). On the other hand, numerous individuals were recorded at the creek for only one minute, including ID 0256 and ID 0185, both of which were observed when TAST was off. Individuals 0075 and 0236 recorded the longest average durations across TAST-off observations (63 min and 40 min respectively), but neither individual was observed during TAST-on observations (Figure 5).

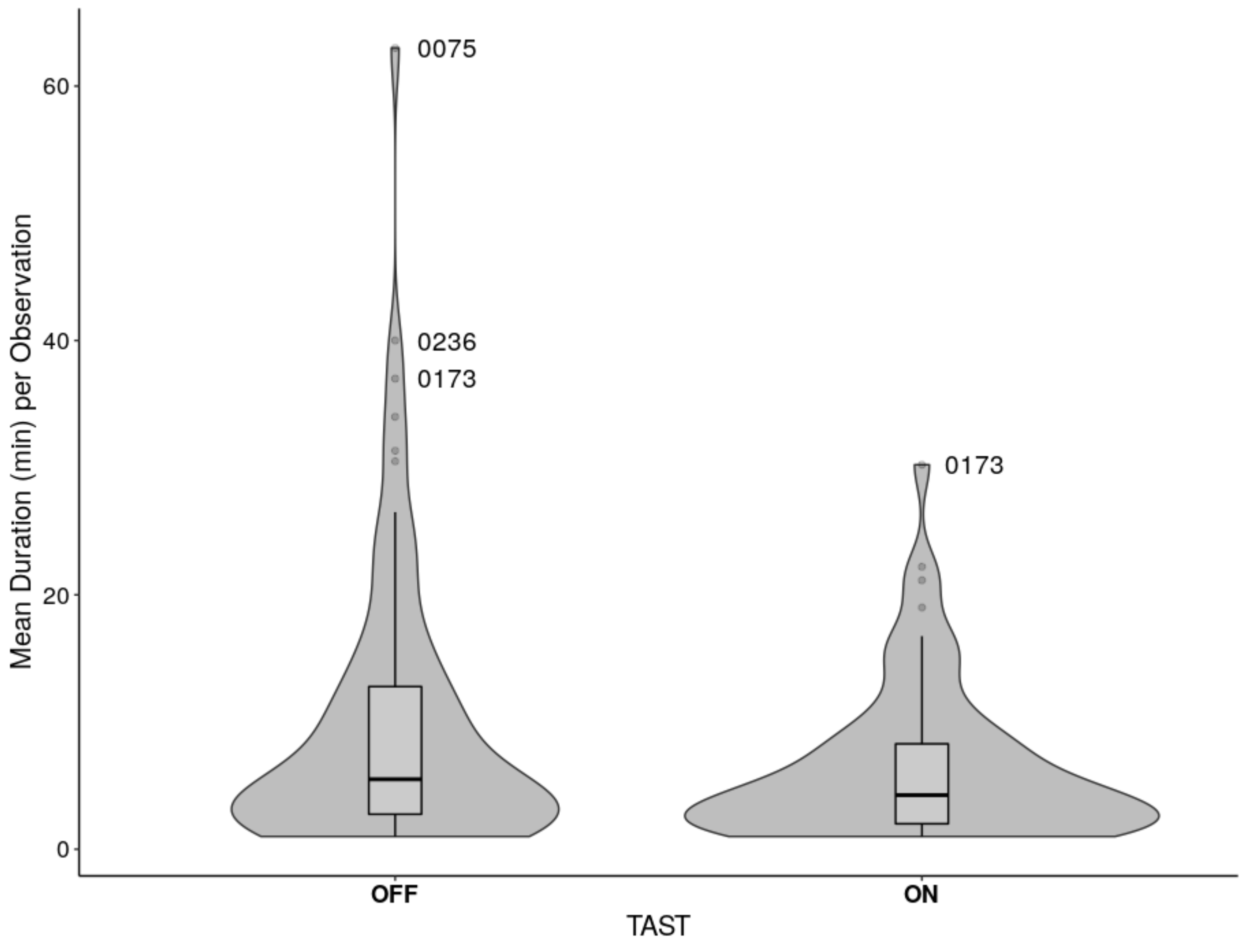

Figure 5. *Violin plots showing the distribution for the average duration (min) that each individual harbor seal remained in the creek across TAST statuses in fall 2020. A boxplot for each distribution is overlaid, showing the median duration across all individuals and the first and third quartile. The three top outliers, IDs 0075, 0236, and 0173 are labeled. IDs 0075 and 0236 were never observed when TAST was on.*

A PERMANOVA test using Bray-Curtis dissimilarity measure indicated that the duration individuals foraged at the creek was significantly different across TAST status ($F_{(1,28)}$= 2.544, p=0.002) (Table 1). Similar results were identified after the removal of singletons, or individuals who were only observed for one min in 2020 ($F_{(1,23)}$= 2.544, p=0.001). NMDS on the duration for each ID per observation showed that dissimilarity was high for observations conducted in fall 2020 (Stress = 0.15). NMDS analysis also showed that observations of seals at Whatcom Creek clustered in ordination space and that the clusters were associated with TAST status (Figure 6). Further, 'envfit' analysis showed that various environmental variables were significantly associated with the clustering of observations, including TAST (r^2=0.14, p= 0.015), tide height (r^2=0.26, p= 0.022), the 5-day rolling average of salmon counts (r^2=0.22, p= 0.033), and the total number of seals present per observation (r^2=0.26, p=0.015). The length of observation (min) and the number of cameras present were not significant environmental variables (r^2=0.05, p=0.51; r^2=0.11, p=0.17 respectively), suggesting added sampling effort from Oceans Initiative did not drive the dissimilarity in duration across observations. Further, PERMANOVA analysis conducted without added observations from Oceans Initiative found similar results, showing that the duration individuals foraged was significantly different across TAST status ($F_{(1,20)}$= 1.75, p=0.034).

Table 1. *Analysis of distance showing the effects of TAST on individual seal presence and duration (min) at Whatcom Creek in 2020. The table was generated using permutational multivariate analysis of variance (PERMANOVA). Bolded p-values denote significance.*

Source of Variation	df	SS	MS	*F*	R^2	*P* value
TAST (on/off)	1	0.85	0.85	2.54	0.08	**0.002**
Residuals	28	9.33	0.33	-	0.92	

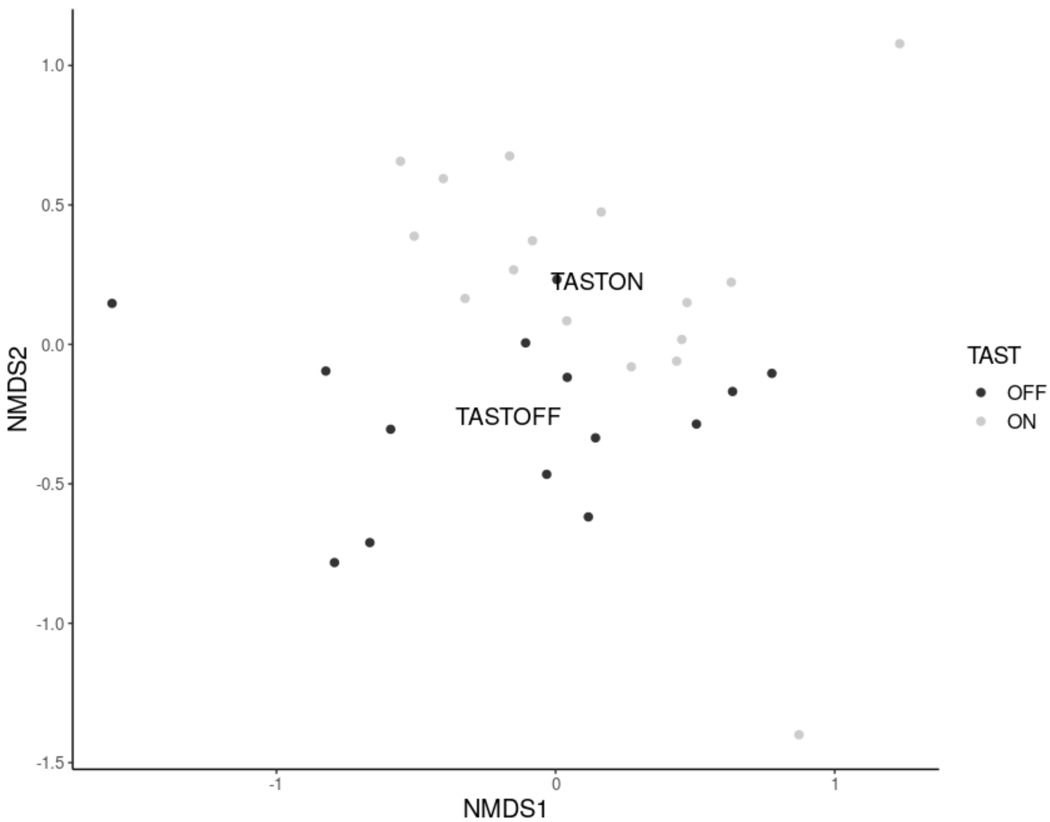

Figure 6. *Nonmetric multidimensional scaling (NMDS) results showing the comparison in individual harbor seal duration at Whatcom Creek. Each data point is a single observation during the experimental window in fall 2020. TAST in overlaid as an environmental factor at the location of the centroids, and gray fill denotes TAST-on and off observations. Stress = 0.15. Two convergent solutions were found after 20 iterations.*

GLMM analysis with negative binomial distribution was used to determine if TAST was a good predictor of individual harbor seal duration in Whatcom Creek. The final, most parsimonious GLMM predicted duration (min) by TAST status (on or off), with seal ID as a random intercept (Table 2). For fall 2020, TAST-on significantly decreased the average duration (min) individuals spent in the creek per observation ($z=-3.773$, $p<0.001$) (Table 3). The estimate for effect size as determined by the model indicate that TAST-on decreased individual duration by 30% compared to TAST-off (Table 3). Seal ID as a random intercept improved model fit and accounted for 42.3% of the variation in the data (Figure S1). The same analysis was conducted using only Marine Mammal Ecology Lab observational data to ensure added sampling effort from Oceans Initiative did not drive the observed effect, and TAST-on still significantly decreased individual seal duration ($z= -2.236$, $p=0.025$).

Of the 98 individuals present during the experimental window, 49 were classified as returning seals and 49 were classified as new seals in 2020. There was no significant association between prior seal fidelity to Whatcom Creek (‘Returners’ vs ‘New’) and the number of days (1-2, 3-4, 5-6, 7+ days) that an individual was present in fall 2020 ($\chi^2=3.59$, $p=0.31$) (Table S1). Further, there was no significant association between prior site fidelity (‘Returners’ vs. ‘New’) and proportion of TAST-on days (0.0-0.24, 0.25-0.49, 0.5-0.74, 0.75-1.0) an individual was observed ($\chi^2=0.47$, $p=0.92$) (Table S2).

Table 2. *Model selection of generalized linear mixed-models (GLMMs) analysis with a negative binomial distribution, degrees of freedom,* R^2*, Akaike Information Criterion (AIC), and delta AIC (ΔAIC) values for duration that harbor seals remained at Whatcom Creek in fall 2020. TAST status (on or off) is included as a fixed independent variable, with 5-day rolling average of salmon counts, tide height, Julian date (n*=27*)*, number of cameras used (n=3), length of observation, and seal ID (n=98) *as potential random intercepts.*

Model	df	R^2	AIC	ΔAIC
Candidate (GLM)				
Duration ~ TAST	3	0.01	2997.1	91.3
Candidate (GLMM)				
Duration ~ TAST + (1|Salmon 5-day average)	4	0.05	2981.5	75.7
Duration ~ TAST + (1|Tide height)	4	0.04	2978.7	72.9
Duration ~ TAST + (1|Date)	4	0.05	2982.1	76.3
Duration ~ TAST + (1|Camera)	4	0.01	2992.6	86.8
Duration ~ TAST + (1|Length)	4	0.06	2981.2	75.4
Final Model (GLMM)				
Duration ~ TAST + (1| ID)	4	0.22	2905.8	0

Table 3. *GLMM with negative binomial distribution output for the final, most parsimonious model describing the total number of* surface *counts (proxy for duration in min) for each individual harbor seals per observation at Whatcom Creek during the experimental window in 2020. Significant p-values (<0.05) are designated in bold.*

Model: Duration (min) ~ TAST + (1|ID)				
Variable	Estimate	Std Error	z-value	P value
TAST ON	-0.352	0.093	-3.773	**<0.001**

Effect on the Foraging Success of Individual Seals

During the 95 observational hours throughout the experimental window, approximately 148 spawning salmon were consumed by 38 individual harbor seals (39% of the 98 seals identified). Of the 38 successful individuals, most (87%) continued to return and forage at Whatcom Creek after being exposed to TAST, with a large proportion (76%) returning across multiple TAST-on observations.

Overall, foraging success varied greatly per individual and was not consistent across TAST status (Figure 7). A total of 55 individual seals were observed foraging at the creek both when the TAST was on and off, 33 of which caught at least one salmon (Figure 7). Of those 33 individuals, 16 (48%) consumed more salmon when TAST was on, 14 (42%) individuals consumed more salmon when the TAST was off, and 3 individuals consumed the same number of salmon regardless of TAST (Figure 7). Eight individuals were only ever observed consuming a salmon when TAST was on, and 7 individuals were only ever observed consuming a salmon when TAST was off (Figure 7).

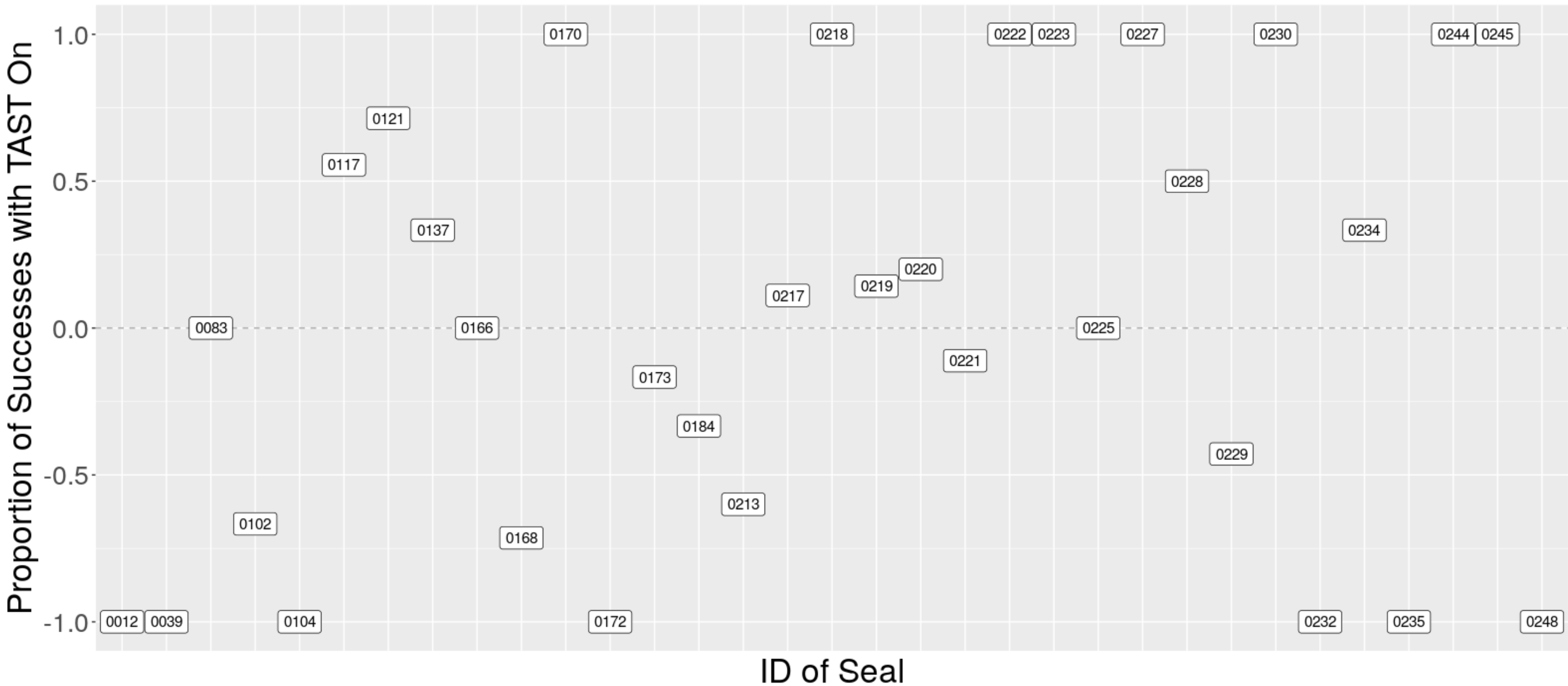

Figure 7. *The proportion of successful predation events with TAST on for individual seals (n=33) during the experimental window at Whatcom Creek in 2020. Proportion is defined as the number of salmon consumed per individual when TAST was on or off out of the total number of salmon consumed for that individual. Positive proportion values indicate a greater proportion of salmon consumed when TAST was ON, whereas negative proportion values indicate a decrease in relative predation successes when TAST was ON. Individuals with a value of +1.0 were only observed consuming salmon when TAST was ON, and individuals with a value of -1.0 were only observed consuming salmon when TAST was OFF.*

The most parsimonious GLMM predicting the total number of foraging successes included TAST and the log-transformed number of days with ID as a random intercept (Table 4). When accounting for the number of days each individual was present, TAST-on significantly reduced the number of salmon caught and consumed by individual seals (n=55, p=0.0165; Table 5). The estimate for effect size as determined by the model indicated that there were 35.5% fewer foraging successes by individuals when TAST was on compared to when TAST was off (Table 5). The log number of days each seal was observed significantly increased the number of salmon caught and consumed by individuals ($p < 0.001$) (Table 5). Seal ID as a random intercept improved model fit and accounted for 44.6% of the variation in the data (Figure S2).

I investigated if prior seal site fidelity to Whatcom Creek ('Returner' vs 'New') was associated with individual foraging success in fall 2020 (successful yes or no) and I found no significant relationship between these two variables (χ^2=1.07, p=0.30; Table S5). Further, there was no significant relationship between prior seal fidelity and when seals caught and consumed salmon across TAST status (χ^2=3.49, p=0.32; Table S6).

Table 4. *Model selection of GLMM analysis for the foraging success of individual harbor seals seen at Whatcom Creek in fall 2020. Number of days observed (nDays)*, *TAST status (on or off)*, and mean observation length (min) *are included as* possible *fixed factors, with ID of individual seals (ID, n=55) included as a random intercept.*

Model	df	R^2	AIC	ΔAIC
Candidate Models (GLM)				
Sum Catches ~ nDays	2	0.216	331.5	58.3
Sum Catches ~ mean Length	2	0.0002	429.2	156.0
Sum Catches ~ TAST	2	0.0002	429.4	156.2
Sum Catches ~ TAST + nDays	3	0.218	330.9	57.7
Sum Catches ~ TAST + log(nDays)	3	0.341	295.6	22.4
Candidate Model (GLMM)				
Sum Catches ~ nDays + TAST + (1|ID)	4	0.767	294.4	21.2
Final Model (GLMM)				
Sum Catches ~ log(nDays) + TAST + (1|ID)	4	0.790	273.2	0

Table 5. *GLMM model output for the final, most parsimonious model describing the total number of salmon caught and consumed by individual harbor seals at Whatcom Creek in 2020. Significant p-values (p<0.05) are indicated in bold.*

Variable	Estimate	Std Error	z-value	P value
TAST on	-0.439	0.190	-2.314	**0.0206**
log(nDays)	1.652	0.222	7.456	**<<0.001**

Long-term Effects of TAST: 2019, 2020, and 2021

During October and December of 2019-2021, 102 observations were conducted for 204 hours. A total of 119 unique individual harbor seals were observed, 41% of which were observed over multiple years. There were several individuals who were only present in one year, with 15 individuals (12.6%) only seen in 2019, 41 (34.5%) only seen in 2020, and 16 (13.4%) only seen in 2021. Of the 119 individuals seen between 2019-2021, 19 (16.0%) were seen in all three years and 13 (10.9%) were seen across both when TAST was on and off in 2020 (Table S3). Of those 13 individuals, only 1 seal (ID 0117) had a successful foraging event across all four TAST statuses (Table S3).

Adult salmon returned to spawn every year during the study, with run size peaking in mid-November (Figure 8). Salmon consistently arrived in mid-October and ran until early December. Between 2019-2021, most salmon that returned were chum salmon (91.9%), however a greater number of Chinook salmon returned in 2021 (50.9% Chinook, 38.7% chum). The run size varied greatly by year, with the greatest number of salmon returning in 2020 (1,885 total chum, Chinook, and coho salmon counted) and the fewest returning in 2021 (395 total chum, Chinook, and coho salmon counted) (Figure 8).

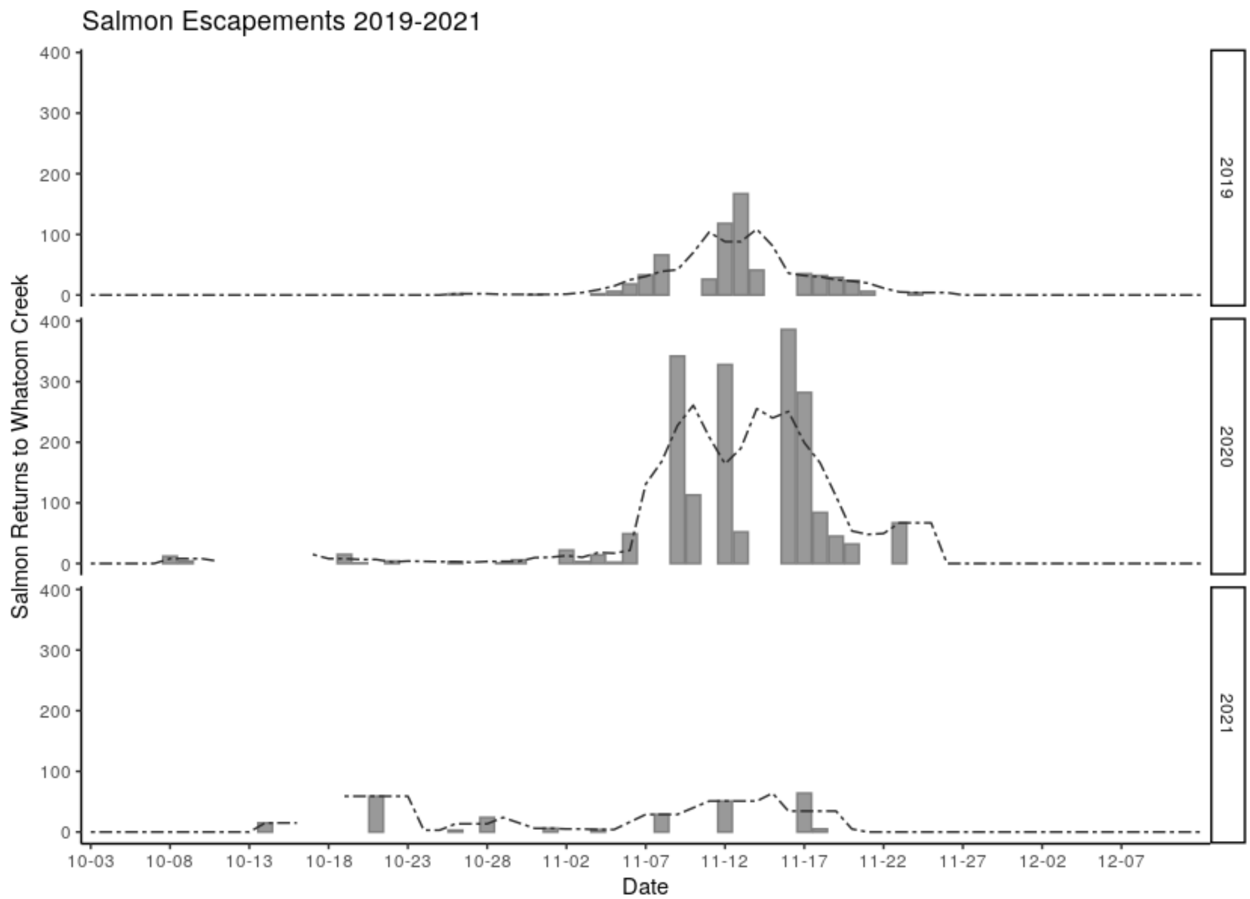

Figure 8. *Total salmon escapement counts at the Whatcom Creek Hatchery between October and December of 2019, 2020, and 2021. Counts include all chum, Chinook, and coho salmon present in the adult holding pool. The 5-day rolling average calculated for each year is overlaid in the black dashed line.*

Effect on Individual Seals

Of the 98 individual harbor seals observed during the TAST experimental window in fall 2020 (October 29th – November 25th), 41 individuals (42%) returned to Whatcom Creek between October and December of 2021. Chi-squared analyses identified an association between TAST exposure in 2020 and the probability that an individual seal would return the following year (2021). All seals that were observed in 2020, including those observed by Oceans Initiative, were classified as either 'not-exposed' or 'exposed' to TAST, with exposure meaning the seals were observed for one or more days while the TAST was deployed and turned on (Table 6). There was a significant association between exposure and likelihood to return, but it was slight ($\chi^2_{(1,n=98)}$ = 3.87, p=0.049; Table 6). Residuals showed that seals exposed to TAST in 2020 were significantly more likely to return in 2021 than expected, whereas seals not exposed to TAST in 2020 were significantly less likely to return in 2021 (Table 6).

Table 6. *Chi-squared test for 2x2 contingency table of exposure level to TAST in 2020 relative to individual seals returning in 2021. 'Exposed' includes all individuals observed for 1 day or more at Whatcom Creek while TAST was on, whereas 'Not Exposed' includes all individuals that were never observed at Whatcom Creek with TAST on. Significant residual values are bolded (>|1.96|). Positive residuals indicate a higher than expected number of returns in 2021, and negative residuals indicate a lower than expected number of returns in 2021.*

	Exposed	**Not Exposed**	Total
Present 2021	33	8	41
Absent 2021	34	23	57
Total Seen in 2020	67	31	98

χ^2	P	Not Exposed:Present	Exposed:Present
3.87	0.049	**-2.188**	**2.188**

Additionally, chi-squared analyses identified a significant association between seal site fidelity and the likelihood an individual would return in 2021 ($\chi^2_{(1,n=98)} = 6.04$, $p=0.014$; Table 7). 'Returners' were significantly more likely to return in 2021 than expected (Table 7). Alternatively, 'New' seals, or seals that were first observed in 2020, were significantly less likely to return in 2021 than expected (Table 7). Of the 49 returners present in 2020, over half (55%) were present in 2021, whereas only 29% of the new individuals present in 2020 returned in 2021.

Table 7. *Chi-squared test for 2x2 contingency table of seal fidelity status in 2020 relative to individual seals returning in 2021. 'New' indicates individuals that were observed at Whatcom Creek for the first time in 2020, whereas 'Returner' indicates individuals that were observed at least once between 2014-2019 at Whatcom Creek. Significant residual values are bolded (>|1.96|). Positive residuals indicate a higher than expected number of returns in 2021, and negative residuals indicate a lower than expected number of returns in 2021.*

	New	**Returner**	Total
Present 2021	14	27	41
Absent 2021	35	22	57
Total Seen in 2020	49	49	98

χ^2	P	New:Present	Returner:Present
6.04	0.014	**-2.66**	**2.66**

Overall, 55 individual seals were observed in 2021, 18 of which (33%) caught and consumed at least one salmon. Of the 18 successful seals in 2021, 16 were present in 2020. Further, 12 of the 18 (67%) successful seals in 2021 had at least one recorded foraging success in 2020. There was a significant positive correlation between catches in 2020 and catches in 2021 ($r_{(112)}$=0.39, p<0.001). When assessed further, there was a significant correlation between number of catches when TAST was off in 2020 and number of catches in 2021 per ID ($r_{(110)}$=0.25, p=0.007). However, there was an insignificant correlation between the number of catches when TAST was on in 2020 and the number of catches in 2021 per ID ($r_{(110)}$=0.17, p=0.07). Chi-squared analysis showed no significant association between TAST exposure in 2020 and the likelihood an individual had at least one successful foraging event in 2021 ($\chi^2_{(1,n=55)}$ = 2.51, p=0.113; Table S4). However, over half (52%) of the individuals who experienced repeat exposures in 2020 (observed for two or more TAST-on days) had a successful foraging event in 2021.

Overall Effect on all Seals

Total seal numbers and total salmon caught by seals were compared across observations during the peak run seasons for 2019, 2020, and 2021. On average, the greatest number of seals foraged at Whatcom Creek in 2020 when TAST was off, compared to the year before (2019), the year after (2021), and when TAST was on (2020) (Figure 9). Similarly, more salmon were consumed on average in 2020 when TAST was off compared to the year before, the year after, and same year when TAST was on (Figure 10).

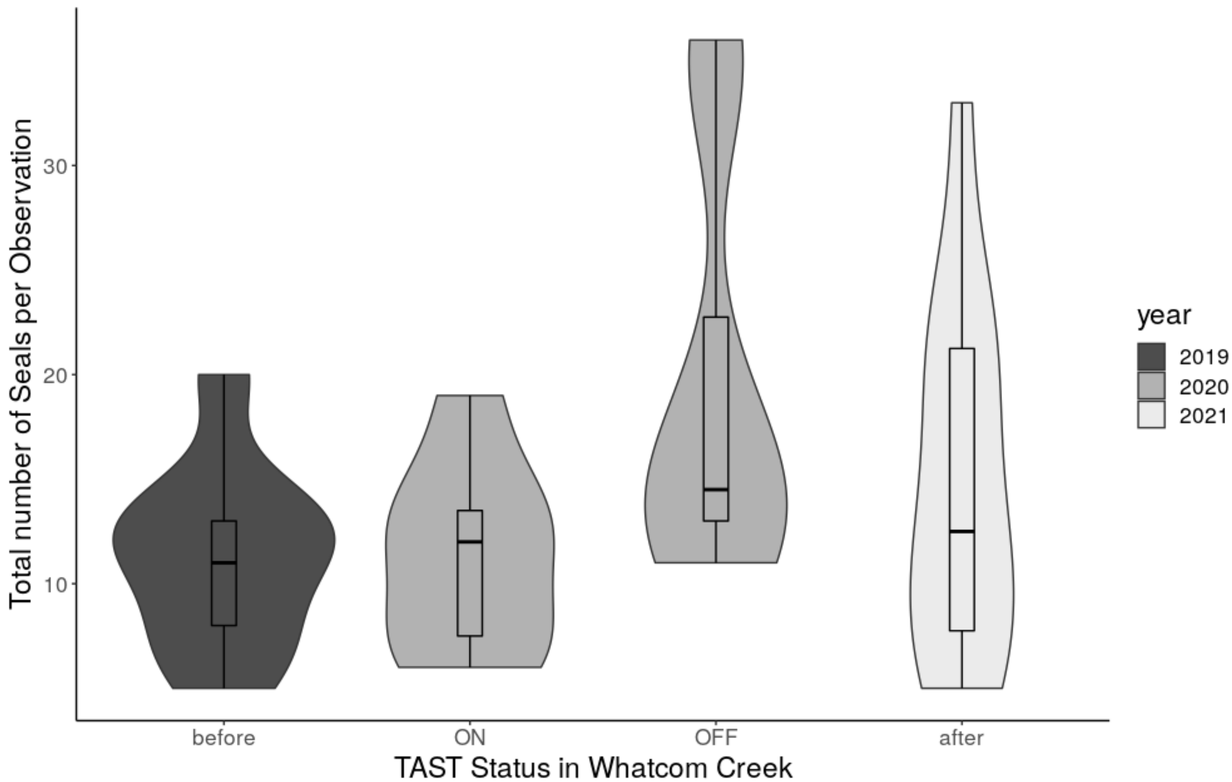

Figure 9. *Violin plots showing the total number of seals observed per observation across each TAST status: before (2019), ON (2020), OFF (2020), and after (2021). Each season is truncated to include only observations in the 20 days around the peak of the salmon run.*

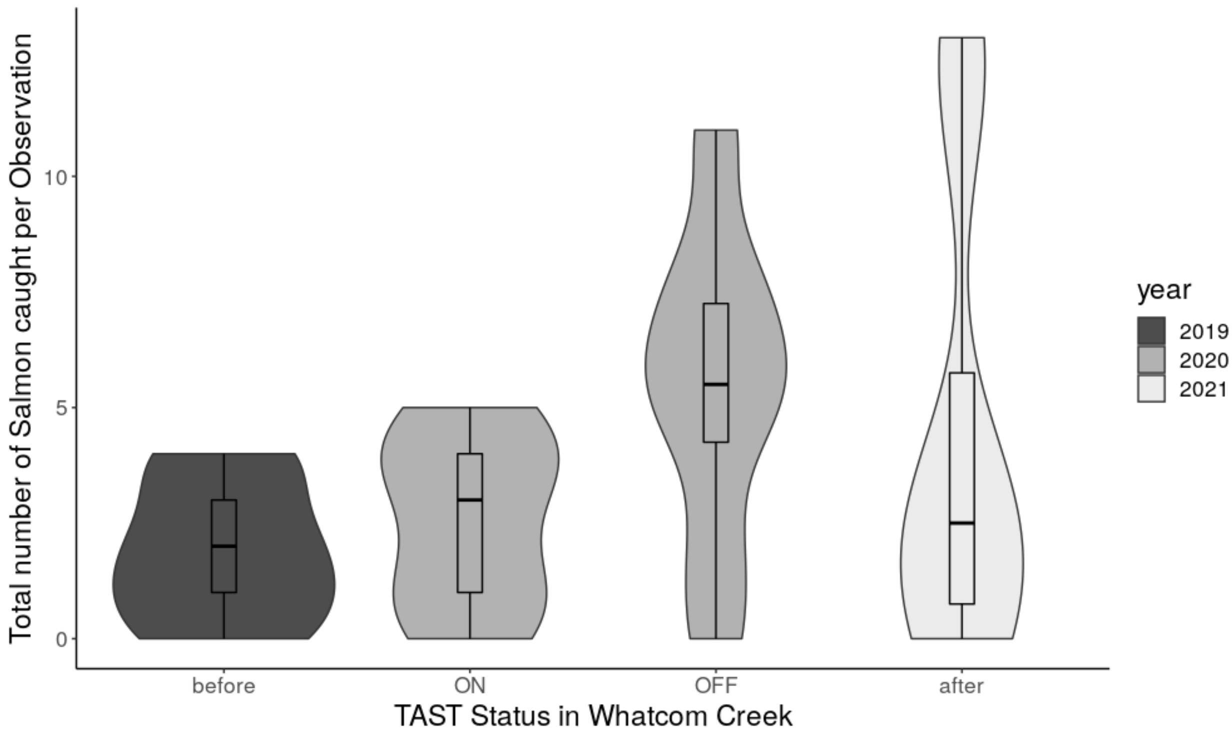

Figure 10. *Violin plots showing the total number of salmon caught by seals per observation across each TAST status: before (2019), ON (2020), OFF (2020), and after (2021). Each season is truncated to include only observations in the 20 days around the peak of the salmon run.*

A GLM analysis with negative binomial distribution showed no significant relationship between TAST and number of seals present per observation during the 2019-2021 peak run seasons (R^2=0.16; Table 8). Further, GLM analysis with binomial distribution showed no significant relationship between TAST and the number of salmon caught per observation during the 2019-2021 peak run seasons (R^2=0.12; Table 9). TAST did not significantly drive the variation in seal numbers or foraging successes observed between years.

Table 8. *GLM with negative binomial distribution output describing the total number of harbor seals observed at Whatcom Creek during the peak salmon runs from 2019- 2021 as predicted by TAST status (before – 2019, on – 2020, off – 2020, after – 2021) .*

Model: Total Seals ~ TAST				
Variable	Estimate	Std Error	t-value	P value
TAST before	-0.2747	0.2068	-1.328	0.184
TAST OFF	0.2615	0.2034	1.285	0.199
TAST ON	-0.2789	0.2239	-1.246	0.213

Table 9. *GLM with negative binomial distribution output describing the total number of salmon caught by all harbor seals per observation at Whatcom Creek during the peak salmon runs from 2019- 2021 as predicted by TAST status (before – 2019, on – 2020, off – 2020, after – 2021).*

Model: Total Salmon Caught ~ TAST				
Variable	Estimate	Std Error	t-value	P value
TAST before	-0.8303	0.4408	-1.884	0.060
TAST OFF	0.2384	0.4081	0.584	0.559
TAST ON	-0.5219	0.4583	-1.139	0.255

Discussion

Short-term Effects of TAST

In the fall of 2020, TAST had a significant impact on individual presence and duration in Whatcom Creek. PERMANOVA and NMDS tests indicated that seal community composition significantly differed across TAST status (on or off), suggesting that TAST was a significant driver of individual seal presence and duration (Table 1, Figure 6). Further, GLMM analysis showed a significant relationship between TAST and the duration that individuals foraged at the creek, with TAST-on decreasing individual duration by 30% compared to TAST-off (Table 3).

While there was a significant impact of TAST on duration (min), several seals continued to return to the creek despite TAST exposure. Throughout the experimental window, 85% of exposed individuals returned to forage at the creek on at least one subsequent observation day, with 67% of exposed seals returning for an additional TAST-on observation (Tables 3 and 4). Notably, IDs 0121, 0172, and 0173 were all observed for 10 or more TAST-on observations after their initial exposure. This suggests that even repeat exposures to TAST did not deter all individuals from returning to the creek, although their average duration may have been reduced with TAST deployed (Figure 5). This is in sharp contrast to 22 individual seals that, after an initial exposure to TAST, were never observed foraging at the creek while TAST was on for the remainder of fall 2020. While it is possible those 22 individuals returned to forage at the creek outside of our observation windows, those visits would have only occurred when TAST was off as all TAST-on periods had observers present. This finding suggests that TAST successfully deterred those individuals from foraging in Whatcom Creek while the device was on.

When comparing the foraging success of all individuals that were observed in Whatcom Creek during experimental conditions (TAST on) and control conditions (TAST off), the effect of TAST was even more variable. Some individual harbor seals were strongly affected by TAST, meaning their foraging success decreased when TAST was on, and others were seemingly unaffected (Figure 7). Contrary to my hypothesis, 16 of the 33 successful seals caught and consumed more salmon when TAST was on, despite being observed foraging in the creek when TAST was off (Figure 7). That said, when I accounted for the number of days each individual was present, TAST-on did have a statistically significant impact on the total number of salmon caught by individuals (Table 5), which aligned with my hypothesis. Critically, seal ID accounted for 44.6% of the variance in the data in the GLMM, further suggesting that the impact of TAST varied greatly across individual seals in fall 2020 (Figure S2).

There are several possible explanations for the observed variability in the effect of TAST on individual harbor seals at Whatcom Creek. First, it is possible that some individuals have compromised hearing from previous sound exposure or old age, rendering the device and any other type of ADD ineffective (Götz & Janik, 2016). This could explain why individuals 0121, 0172, and 0173 were seemingly unaffected and continually returned to Whatcom Creek while the device was on. Similar hypotheses were made in previous studies of TAST, including at Ballard Locks where there is heavy use of other pain-inducing ADDs, such as seal bombs and firecrackers, which may compromise the hearing of harbor seals and minimize the potential effects of TAST (Bogaard, 2021; Williams, Ashe, Bogaard, et al., 2021). Anecdotally, there was no recorded use of pain-inducing ADDs at Whatcom Creek during this study or in prior years, so it is unlikely that individuals in our study were exposed to damaging sound levels at Whatcom Creek. However, the use of pain-inducing ADDs around Bellingham Bay and in the Salish Sea is not well documented, so it is possible that individuals in this study were exposed to damaging sound levels elsewhere. Other sources of anthropogenic or natural sound may impact pinniped hearing as well, such as noise generated by sub-bottom profiling sonars, vessels, pile driving, etc. (Hastie et al., 2021; Polagye & Bassett, 2020). Future studies should try to confirm if individuals that are less affected by TAST (e.g., IDs 0121, 0172, 0173) are in fact hearing impaired, although this may be logistically difficult.

The variable effects of TAST may also be due to transmission loss within the creek, reducing the effective range. A similar study of TAST at Ballard Locks found that received levels at 50 m from the device were just below the startle threshold for a seal with good hearing (159 dB), despite the device previously showing deterrence effects up to 250 m in the study by Götz & Janik (2016) (Bogaard, 2021; Götz & Janik, 2011; Williams, Ashe, Bogaard, et al., 2021). Researchers from Oceans Initiative measured received levels of the TAST signal in Whatcom Creek and found that levels were below the startle threshold at 50 m from the device (Williams, Ashe, Reiss, et al., 2021). River environments often have higher ambient noise due to flowing water and can be shallow with varied bottom-profiles, all aspects that may affect sound transmission and impact the effective range of ADDs (Ellison et al., 2012; Graham et al., 2009; Harris et al., 2014; Williams, Ashe, Bogaard, et al., 2021). At Whatcom Creek, transmission loss may have allowed some individuals to remain and forage in the area, even with the device actively deployed.

Additionally, individuals may be taking advantage of acoustic shadows in the creek, or areas where sound levels are not strong enough to elicit a startle response due to physical barriers disrupting sound transmission. TAST was deployed at the base of the hatchery fish ladder, which is located at a removed spot on the west bank of the study site (Figure 1). There is a concrete wall that runs from the ladder all the way to the upper falls, in the northeast portion of the study area (Figure 1). The concrete wall forms a sharp corner at observation location B (Figure 1).

Observers noted many harbor seals foraging upstream, north of observation location B, a location hereby referred to as the 'upper river'. Notably, the individual that caught the greatest number of salmon in fall 2020, ID 0217, caught many of its fish in the upper river. For example, ID 0217's most successful day was on 11/20/2020 in which 0217 caught at minimum 4 salmon in a single 2-hour period. TAST was deployed and on throughout the observation on 11/20/2020, and observers recorded all catches by ID 0217 as occurring in the upper river. It is likely that the upper river, which is both upstream from the device and behind a concrete wall, is within an acoustic shadow, allowing individuals to forage regularly with the device on. In fact, recordings of received levels of the TAST signal showed significant transmission loss in the upper river, only 26-30 m from the device (Williams, Ashe, Reiss, et al., 2021). Similar acoustic shadows, or 'shadow zones', have been observed in other study systems and should be considered when developing a deployment strategy (Götz & Janik, 2016; Jacobs & Terhune, 2002).

As is often a problem with ADDs, the motivation to forage may be stronger than the aversiveness of the device in our study site. Previous studies report that harbor seals swim past active ADDs if the motivation exists to do so (Graham et al., 2009). If the abundance and availability of prey is a strong enough motivator, individual seals may be able to ignore ADDs and continue to forage (Graham et al., 2009; Jacobs & Terhune, 2002; Yurk & Trites, 2000). This behavioral drive, combined with possible transmission loss or acoustic shadows, might allow some individuals to remain in the creek and forage even with TAST operating.

Additionally, if seals have had prior experience successfully foraging at Whatcom Creek, they may be more likely to return and/or continue to forage despite deterrent efforts. For example, studies at Bonneville Dam have shown that the highly concentrated abundance of salmon near the dam tailrace and fish ladder was a strong attractant to pinnipeds, which in turn made deterrent efforts difficult and habituation more likely once the pinnipeds arrived at the dam and began foraging (Tidwell et al., 2021). At Whatcom Creek, 18 harbor seals were observed foraging on salmon prior to TAST deployment in 2020, and 17 returned during the TAST experimental window. Five of those individuals were observed consuming salmon prior to TAST deployment, and all 5 returned during the experimental window, with 4 of the 5 recording additional successful events. It is possible these individuals experienced the benefit of foraging at Whatcom Creek, and therefore the motivation to remain and forage was higher than the aversion caused by TAST.

Previous studies on pinnipeds preying on spawning salmon have shown a phenomenon of nuisance or problem individuals who repeatedly return to a river and forage over consecutive years (Freeman et al., 2022; Scordino, 2010). Similar trends have been observed at Whatcom Creek, with a majority of identified seals returning over multiple years between 2014 – 2021 (Freeman et al., 2022). Interestingly, half (50%) of the individuals identified within the experimental window in 2020 were new seals, meaning they had never been observed at Whatcom Creek prior to fall 2020. This proportion of new individuals in 2020 was larger than the proportion observed in 2019 (23% new) and in 2021 (24% new). Further, out of the 7 individuals that were 100% more successful with TAST on, 5 were new individuals.

This influx of new individuals to Whatcom Creek may have been caused by the introduction of TAST. For example, it is possible that some less successful returning seals were deterred, leaving an ecological gap for new individuals to fill and benefit from. Alternatively, ADDs are often associated with a ‘dinner bell effect’, meaning predators learn to associate the deterrent sound with prey availability (Schakner & Blumstein, 2013). The received sound level of the TAST signal was well below the startle threshold at the mouth of Whatcom Creek (approximately 124 dB), so individuals would need to enter the creek to experience the deterrent effects (Williams, Ashe, Reiss, et al., 2021). Therefore, it is possible the novel sound signal acted as a dinner bell and attracted new, curious individuals rather than deterring them. However, there was no significant association between prior seal fidelity status (new vs returner) and the number of days an individual was observed (Table S1) or when they were observed in relation to TAST (Table S2). Further, there was no significant relationship between seal fidelity status and foraging successes in fall 2020 (Table S5), and there was no significant relationship between seal fidelity status and when the foraging success or successes occurred with regards to TAST (Table S6).

Rather than TAST driving this shift, it is possible the larger proportion of new individuals observed was due to increased observational effort from Oceans Initiative in 2020. Oceans Initiative observed for several hours throughout the high tide during TAST deployment, which differed from Marine Mammal Ecology Lab's observation protocol in 2019 and 2021 (2-hour observations around slack tide). It is possible that more new individuals were observed simply because observations occurred at different times within the creek. Without including any observations from Oceans Initiative, there still remained 47% new individuals (41 out of 86 seals) observed during the experimental window, greater than seen in 2019 or 2021. It is unclear what caused this increase of new seals observed, but it would be interesting to see if a similar pattern occurred if TAST were redeployed at Whatcom Creek in another year.

It is possible harbor seals delayed their foraging efforts when TAST was on and took advantage of any off-periods throughout fall 2020. The deployment of TAST followed a Controlled Exposure Experimental design (Tyack et al., 2003), as explained in Williams, Ashe, Reiss, et al. (2021) and Bogaard (2021). The motivation behind this unbalanced design (3-days on, 1-day off) was to fulfill Oceans Initiative's commitment to adaptive management, meaning that if TAST did successfully deter harbor seals from eating salmon, they would be mitigating three times more than collecting control data. This design allowed for direct comparison between experimental treatment (TAST on) and control days (TAST off) throughout the peak of the 2020 salmon run season. However, it did provide days of reprieve in which seals could return and forage when TAST was off, avoiding the deterrent system. When assessing all observations conducted by the Marine Mammal Ecology Lab, including observations conducted in October and December, 34 individuals were only observed foraging when TAST was off, and 12 individuals were observed for one TAST-on observation and subsequently only returned when TAST was off. This suggests a certain degree of selectivity, in which some individuals continued to return to Whatcom Creek to forage, but only when the device was off.

Further, TAST was not deployed for 24 hours, but rather for an average of 4 hours (SD= 0.97h, n=18) around high tide. While harbor seals do reliably aggregate and forage during daylight hours, studies in other systems report high rates of nocturnal foraging on salmonids in rivers (Wright et al., 2007; Yurk & Trites, 2000). Due to limitations of availability and observer safety, observations only occurred during daylight hours. It is likely that harbor seals continued to forage at dusk and during the night, when TAST was not operating. It is therefore possible that seals took advantage of these TAST-off periods and simply delayed their foraging efforts when TAST was on. Similar results were gathered by Götz and Janik (2016) when testing TAST at several aquaculture farms in Scotland. One site showed ambiguous results with no significant decrease in seal predation on salmon, possibly due to temporary off periods during deployment (Götz & Janik, 2016). Other studies of ADDs report that seals may take advantage of temporary off periods or lapses in the device (Graham et al., 2009; Harris et al., 2014). Therefore, to be most effective, TAST should remain on and operating when utilized as a management tool to mitigate all foraging efforts.

Lastly, it is possible that seals foraged in alternate deterrent-free locations while TAST was deployed (Trites & Spitz, 2016). Individuals that typically forage at Whatcom Creek may have found other nearby river systems to prey on spawning salmon, thereby avoiding the effects of TAST while still impacting Pacific salmon populations. No observations were conducted at other river sites in fall 2020, so it is unknown if individuals from Whatcom Creek foraged in alternate locations while TAST was operating. Future research would need to consider the potential detrimental effects on alternate foraging grounds when deploying TAST at a site of concern.

Long-term Effects of TAST

My study found no detectable long-term effects of TAST on presence or foraging success of individuals in 2021. Thirteen individuals were observed in 2019, 2020 with TAST on, 2020 with TAST off, and in 2021 (Table S3). The proportion of days observed and the number of catches per individual varied greatly across year and across TAST status (Table S3). In the long-term, there was no clear signal showing that TAST had an impact on individual seal foraging success. There was no significant association between TAST exposure in 2020 and individual foraging successes in 2021 (Table S4). Rather, there was a significant correlation between successful seals in 2020 and successful seals in 2021. This suggests that the number of salmon consumed by individuals was similar across these two seasons, despite TAST being deployed in 2020.

There was a significant relationship between TAST exposure in 2020 and the likelihood that an individual would return in 2021, however the relationship was contrary to expectations. Fewer individuals with no observed exposure to TAST returned to the creek in 2021 than expected

(Table 6). On the other hand, more individuals with exposure to TAST returned in 2021 than expected (Table 6). It is possible those individuals were deaf or benefitted from acoustic shadows, as discussed in the previous section, and therefore were able to avoid a fear-conditioned response to TAST that would lead to long-term learned avoidance (Götz & Janik, 2011; Schakner & Blumstein, 2013). However, this does not explain why individuals with no exposure to TAST were less likely to return to the creek.

Alternatively, it is possible that there are other drivers influencing which individuals return to forage at Whatcom Creek each year. The best predictor for the likelihood an individual would return in 2021 was their previous fidelity to Whatcom Creek (Table 7). Individuals who were new to the creek in 2020 were less likely to return in 2021, whereas individuals who had been seen prior to 2020 were more likely to return again in 2021, regardless of TAST exposure (Table 7). The 7 individuals that had the most observed exposure to TAST in 2020 (7 or more days) all returned in fall 2021, and 5 of the 7 had been observed foraging at Whatcom Creek multiple times between 2014-2019.

These data suggest that long-term patterns in the presence of individuals across years may be driven more by foraging site fidelity than by TAST. Harbor seals are central place foragers, meaning they exhibit strong site fidelity and often forage close to their haul-out sites (Cordes & Thompson, 2015; Cunningham et al., 2008; Grigg et al., 2012; Iorio-Merlo et al., 2022). Although harbor seal fidelity to haul-out sites is well understood (Cordes & Thompson, 2015), there is limited knowledge of across year harbor seal fidelity to specific foraging sites. Iorio-Merlo et al. (2022) found that individual harbor seals repeatedly used the same foraging areas over time, suggesting that both memory and prey encounters influence an animal's foraging decisions. Similar patterns of foraging site fidelity have been observed in other pinnipeds, including: elephant seals (*Mirounga* spp.) (Bradshaw et al., 2004; McIntyre et al., 2017), Australian fur seals (*Arctocephalus pusillus doriferus*) (Knox et al., 2018), Antarctic fur seals (*A. gazella*) (Arthur et al., 2015; Bonadonna et al., 2001), and gray seals (S. M. Oksanen et al., 2014). At Whatcom Creek, a high percentage of seals identified (56.5%) were repeat visitors, meaning they were observed during more than one year between 2014-2021 (Freeman et al., 2022). For example, ID 0039 has been observed every year during the salmon run at Whatcom Creek since 2014 (Freeman et al., 2022).

My results suggests that seal fidelity to foraging site has a strong influence on the likelihood an individual will return the following year, trumping the potential long-term deterrent effects of TAST. I hypothesize Whatcom Creek is nearby the central place (haul-out site) for those individual seals that routinely return and forage within a season and across years. When alternative foraging sites are limited, harbor seals may tolerate or habituate to disturbances, such as TAST, to continue using the profitable foraging site near their central place (Grigg et al., 2012). Exposure to TAST in 2020 did not deter seals from returning to the profitable foraging site in 2021, especially for individuals who were repeat-visitors and frequently return to forage year after year. That said, this comparison between the deterrent effects of TAST and the fidelity of individuals to foraging site would be better assessed by comparing two consecutive years of experimental treatment. Future studies should deploy the device over two years to determine if individuals habituate to the device or if site fidelity is altered by continued deployment. With two years of TAST deployment, researchers could determine if the device is effective at deterring individual seals familiar with the benefits of the foraging location.

To assess this interplay between foraging site fidelity and the likelihood an individual would return in 2021, I categorized seals as either new to Whatcom Creek or as returners.

However, this categorization relied on data from previous observations at the creek conducted during daylight hours from October – December of each year. It is possible certain individuals foraged outside of our observation windows, meaning they were not identified as present in previous years, affecting their status as either a new or returning seal in my study. Regardless, there is a large contingency of individuals who routinely return to Whatcom Creek to forage and did so even with TAST deployed.

The long-term effects of TAST were assessed across the general population of seals present between the peak run seasons in 2019, 2020, and 2021. The greatest median number of seals were observed foraging and the greatest median number of salmon was consumed during TAST-off observations in 2020 compared to other years (Figure 9, Figure 10). TAST-on observations in 2020 had similar numbers of seals present and similar numbers of foraging successes as observations in 2019 and 2021, contrary to the hypothesis (Figure 9, Figure 10). It is possible that seals took advantage of TAST off days and simply delayed their foraging efforts when TAST was on, as was discussed in the previous section. Alternatively, it is possible that there was a delayed 'dinner bell effect' in fall 2020, with more seals coming to the area to forage but waiting until the device was off to remain and feed. Either case could have resulted in the higher-than-normal number of foraging events recorded during TAST-off observations in 2020 compared to 2019 and 2021. However, when assessed statistically, TAST was not a significant driver of variation in seal numbers of salmon consumed between years (Table 8, Table 9).

There was inherent variability between the years in my study that made assessing the long-term effects of TAST difficult. For example, prior research showed that the number of fishers present at the creek significantly predicted the odds that an individual seal would have a successful foraging event (Freeman et al., 2022). However, the number of fishers present from

2019 – 2021 was highly variable due to the regulated fishing season. The salmon fishing season was open at Whatcom Creek in 2019 and an average of 13 fishers were present per observation (SD=7.4) during the peak salmon run. On the other hand, the season was closed to fishers in 2020 and 2021, resulting in no fishers present during observations. The lack of fishers present at Whatcom Creek may have impacted seal presence and foraging successes in 2020 and 2021, compared to 2019. That said, the average number of seals present and average number of salmon consumed was similar between 2019 and 2021, so it is unlikely this had a significant effect.

Further, weather may have played a role in the variability across years. In November 2021, there was a significant flooding event in the middle of the chum salmon run, causing heavy creek flow and low salmon returns (Figure 8). High water flow increased water turbidity in the creek, possibly impacting the visual acuity of seals foraging on salmon (Weiffen et al., 2006). This, in turn, may have impacted which seals were present, how many were present, and how much salmon was available to consume. Lastly, the fall adult salmon run has greatly declined at Whatcom Creek over the past decade (Freeman et al., 2022). Due to lower chum returns, the Whatcom Creek Hatchery has shifted to primarily rearing Chinook salmon, resulting in higher Chinook runs and lower chum runs in the last year of the study. This shift in run timing and run size may have impacted which seals were present, how many were present, and how much salmon was consumed.

This variability between years made it difficult to discern any lingering effects of TAST from other ecological drivers of variation. However, data show that 2019 and 2021 were similar across the general population of seals, despite the variation in salmon availability, number of fishers present, extreme weather, or TAST deployment. My results suggest that there is no meaningful long-term effect of TAST over multiple years. In other words, there was no evidence of a long-term fear-conditioned response caused by TAST in 2020 that deterred individuals from foraging again in 2021. Therefore, TAST needs to be actively deployed to effectively deter harbor seals from consuming salmon in Whatcom Creek.

Management Implications

TAST was effective at deterring seals during observations throughout fall 2020 but was ineffective beyond that season. Within the experimental season, effects were variable across individuals, suggesting the device is not a one-size-fits-all solution. While it did significantly decrease the duration seals remained in the creek and the number of salmon caught and consumed by seals, there was significant variation between individuals, with some strongly affected and others unaffected. When individual variability was considered, the effect of TAST was diminished compared to other studies assessing the general population of seals (Götz & Janik, 2016; Williams, Ashe, Bogaard, et al., 2021; Williams, Ashe, Reiss, et al., 2021). Further, my study observed no meaningful lingering effect of TAST in the year after deployment. For TAST to be an effective management strategy in the long-term, there needs to be regular reinforcement to condition an avoidance behavior strong enough to overcome the observed site fidelity exhibited by individual seals.

The management of pinniped predation on depleted salmon stocks is a complex problem that will require a multifaceted solution (Bowen & Lidgard, 2013; Morissette et al., 2012; NMFS, 1997; Scordino, 2010). This study presents encouraging results, showing that TAST is an effective management tool in deterring most harbor seals from preying on adult salmon when actively deployed. However, TAST had no long-term effectiveness across years, and there was strong variability amongst individual seals. It is possible that, by deploying a network of coordinated TAST devices throughout the study site, managers could reduce the likelihood of acoustic shadows or the loss of transmission and thereby increase the effectiveness of the deterrent. Further, in-air playbacks of the device could help mitigate avoidance strategies, such as swimming at the surface to avoid the sound stimuli (Bogaard, 2021; Williams, Ashe, Bogaard, et al., 2021). Lastly, deploying the device continuously, rather than having off-periods, could help mitigate an influx of delayed foraging attempts by seals (Götz & Janik, 2016).

However, this approach does not address the individual variation amongst seals, such as the issue of hearing-compromised individuals or strongly motivated 'problem' individuals. Direct observational studies such as this one have shown that relatively few individual pinnipeds are responsible for a majority of the predation on salmon at specific sites (Freeman et al., 2022; Scordino, 2010). Selective lethal removal of problem individuals, albeit controversial and contentious (Cummings et al., 2019; Jackman et al., 2018; Keefer et al., 2012; Scordino, 2010), may help reduce the pinniped-fishery conflict and mitigate predation on depleted salmon stocks (NMFS, 1999; Scordino, 2010). It is possible that individual-specific management methods, such as lethal removal or translocation, and general management methods, such as building physical barriers or deploying TAST, could be used in tandem to mitigate pinniped predation pressures. Future studies should assess the effects of various multi-faceted pinniped management strategies at sites of concern. Further, management of pinniped predation should be done in conjunction with long-term ecosystem restoration and stock-specific management efforts to directly aid depleted salmon stocks (Sobocinski et al., 2021).

Overall, this study suggests that management of pinnipeds should consider individual variability in foraging success. When deployed, TAST can be a helpful tool in deterring pinnipeds, but it is not equally effective across all individuals. It should be used in addition to other management methods at a site of concern to mitigate predation pressures and allow for prey recovery.

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Appendix

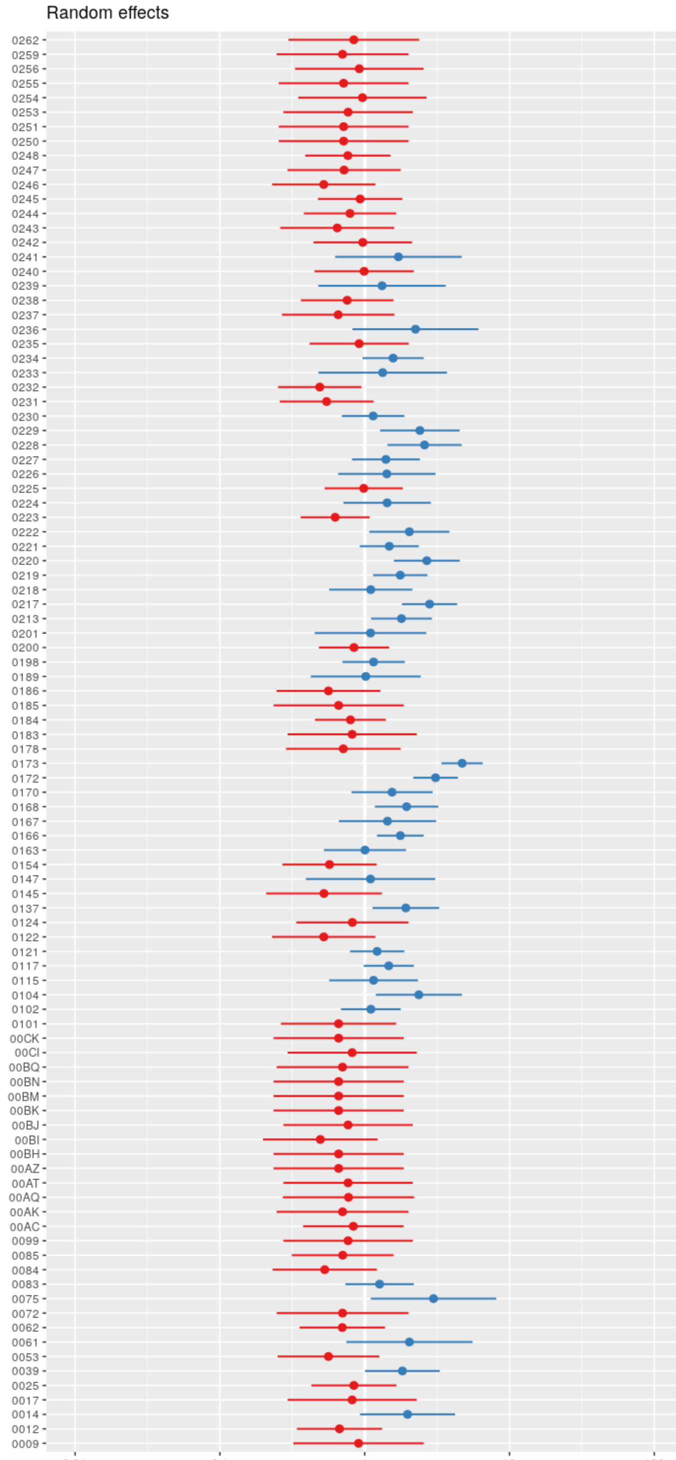

Figure S1. *Plot showing the variation among the levels of the random effect (seal ID) for the final GLMM predicting duration (min) of seals at Whatcom Creek in 2020. Y-axis shows each individual seal (n=98) and the values indicate the difference between the general model estimate and individual effect. Color denotes either a positive (blue) or negative (red) relationship to the general model intercept for each seal. According to estimates, IDs 0173, 0172, and 0075 spent the most time at Whatcom Creek in fall 2020.*

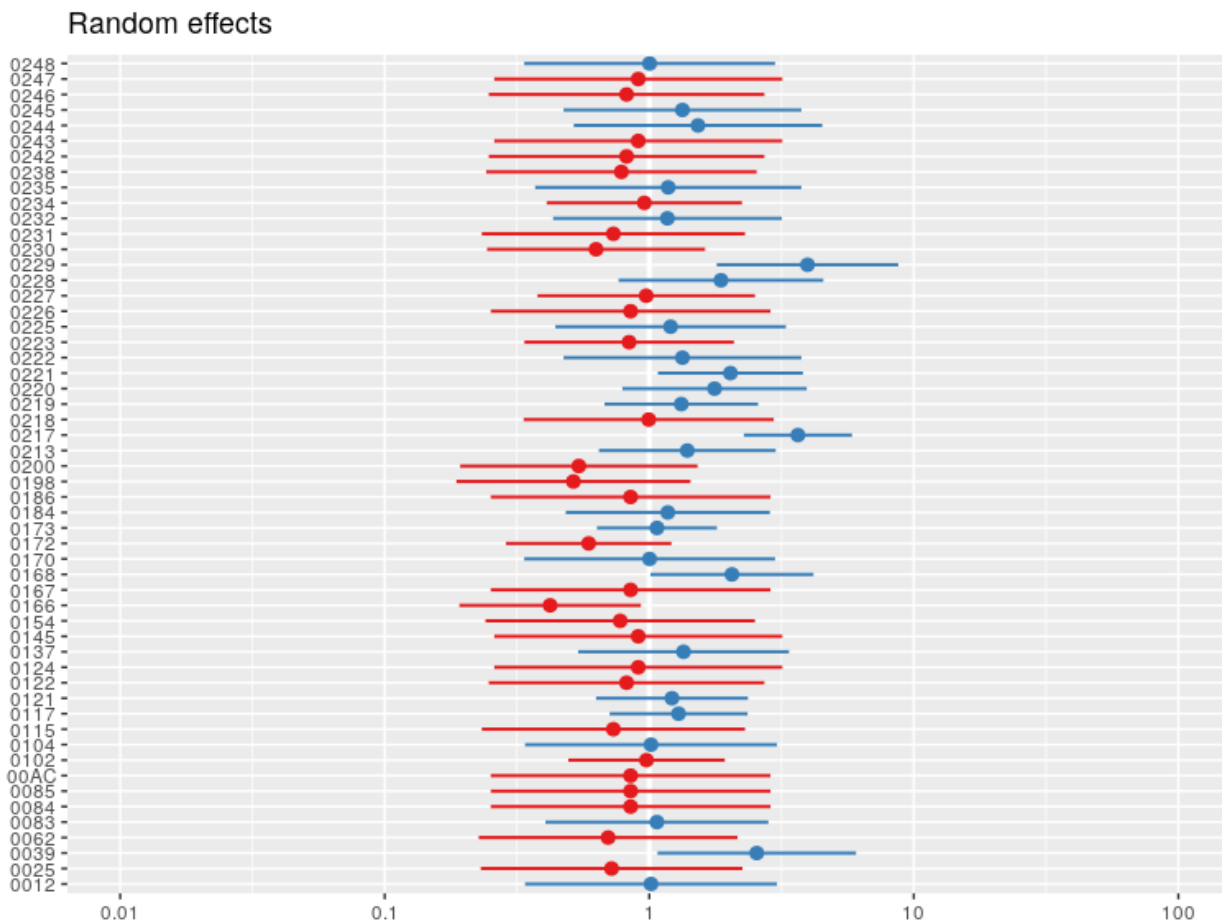

Figure S2. *Plot showing the variation among the levels of the random effect (seal ID) for the final GLMM predicting sum of salmon caught by seals at Whatcom Creek in 2020. Y-axis shows each individual seal (n=55) and the values indicate the difference between the general model estimate and the individual effect. Color denotes either a positive (blue) or negative (red) relationship to the general model intercept for each seal. According to estimates, IDs 0229, 0217, and 0039 consumed the greatest number of salmon in fall 2020.*

Table S1. *Chi-squared test for 2x4 contingency table, comparing seal fidelity as it relates to number of days observed for each individual seal in fall 2020. Chi-squared statistics (χ^2), p-values, and Pearson's residuals are shown for seal site fidelity status and number of days present in 2020.*

	New	**Returner**	Total
1-2 Days	26	17	43
3-4 Days	10	12	22
5-6 Days	5	7	12
7+ Days	8	13	21
Total Seen in 2020	49	49	98

χ^2	P	New:1-2 Days	New:3-4 Days	New:5-6 Days	New:7+ Days
3.589	0.309	1.832	-0.484	-0.616	-1.23

Table S2. *Chi-squared test for 2x4 contingency table comparing seal fidelity as it relates to proportion of days observed when TAST was on out of the total number of days observed for each individual seal.*

	New	**Returner**	Total
0.0-0.24	19	16	35
0.25-0.49	5	6	11
0.5-0.74	15	17	32
0.75-1.0	10	10	20
Total Seen in 2020	49	49	98

χ^2	P	New: 0.0-0.24	New: 0.25-0.49	New: 0.5-0.74	New: 0.75-1.0
0.473	0.925	0.632	-0.320	-0.431	0.000

Table S3. *Proportion of days observed and total number of salmon caught per ID for seals seen across all four TAST status: before (2019), On (2020), Off (2020), and after (2021). Proportions are the number of observations each seal was present out of the total number of observations conducted per year between October and December.*

	2019		2020				2021	
	Before TAST		TAST On		TAST Off		After TAST	
ID	Days Observed	Total Catches	Days Observed	Total Catches	Days Observed	Total Catches	Days Observed	Total Catches
0012	0.48	0	0.07	1	0.42	0	0.35	0
0039	0.30	3	0.07	6	0.54	0	0.62	14
0083	0.30	2	0.07	1	0.25	0	0.19	4
0085	0.04	0	0.07	0	0.17	0	0.24	2
0117	0.19	1	0.29	2	0.33	1	0.43	5
0121	0.04	0	0.29	0	0.08	1	0.35	4
0166	0.30	0	0.29	1	0.63	0	0.41	0
0172	0.07	0	0.36	3	0.29	0	0.35	1
0173	0.30	0	0.57	6	0.38	4	0.19	2
0186	0.07	0	0.14	0	0.04	0	0.27	0
0198	0.15	2	0.14	0	0.21	0	0.16	3
0200	0.11	3	0.21	0	0.04	0	0.03	0
0213	0.07	0	0.29	3	0.08	1	0.05	0

Table S4. *Contingency table and resulting Chi-squared test for 2x2 table comparing seal exposure to TAST in 2020 and the individual's foraging success in 2021 for all seals present in 2021 (n=55).*

	Exposed	**Not Exposed**	Total
Foraging Success	14	4	18
No Foraging Success	19	18	37
Total seen in 2021	33	21	55

χ^2	P	Exposed:Success	Not_Exposed:Success
2.51	0.113	1.88	-1.88

Table S5. *Contingency table and resulting Chi-squared test for 2x2 table comparing seal fidelity status to successful foraging events (yes or no) in 2020 for each individual present in 2020 (n=98).*

	New	**Returner**	Total
Foraging Success	16	22	38
No Foraging Success	33	27	60
Total Seen in 2020	49	49	98

χ^2	P	New:Success	Returner:Success
1.07	0.299	-1.244	1.244

Table S6. *Contingency table and resulting Chi-squared test for 2x4 table comparing seal fidelity as it relates to successful foraging events across TAST status in fall 2020. Successes were categorized per individual according to when the success or successes were observed: only when TAST was on (Success_On), only when TAST was off (Success_Off), both when TAST was on and off (Success_both), or no observed success (Success_none*).

	New	**Returner**	Total
Success_On	6	4	10
Success_Off	3	7	10
Success_Both	7	11	18
Success_None	33	27	60
Total Seen in 2020	49	49	98

χ^2	P	New:Success_on	New:Success_off	New:Success_both	New:Success_none
3.489	0.322	0.667	-1.334	-1.043	1.244