Size selection of red king crab (*Paralithodes camtschaticus)* and behavioural response to experimental pot designs

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Abstract

Today, the Norwegian red king crab (*Paralithodes camtschaticus)* fishery is commonly using collapsible single-chamber pots. Although the use of escape openings is enforced in the quota regulated area, the fishery is experiencing large bycatches of undersized (CL < 130mm) crabs. Handling bycatch on deck is time consuming and can lead to handling induced injuries and mortality, which is a concern for future landings and animal welfare. Therefore, the red king crab fishery requires improved pot design with a size selective mechanism that can either prevent small crabs from entering the pot or facilitate increased escape of undersized crabs at fishing depth. In this study, I investigated the red king crab (RKC) behaviour in relation to selection mechanisms in two experimental pot designs under controlled laboratory conditions. Pot design one aimed at preventing undersized crabs from entering via the addition of slippery panels to the entrances (pot 1). Pot design two aimed at stimulating undersized crabs to escape at fishing depth (pot 2). This was achieved by adding a bottomless chamber beneath the main chamber, which was connected to the main chamber by escape openings and supplied with bait to motivate the crabs to descend into the bottomless chamber. One of the aims of this study was to determine the effectiveness of a slippery panel as a size selective barrier and if behaviour affected probability of entry. Therefore, a comparative study with a control pot without a slippery panel was used. An additional aim was to investigate the effectiveness of the second chamber, if undersized crab escaped to the bottomless chamber and did not return to the main chamber. Pot 1 displayed size selective properties, where mean CL was significantly higher for the crabs that successfully entered the pot than those that failed (Welch's t-test, df = 56.121, p = 0.00025), and CL was found to have a significant effect on modelled probability of entry (L50 = 124mm, SR = 43mm) (GLM, p = 0.00139). Additionally, three behaviour categories were also observed to affect the probability of entry, for all carapace lengths. Crabs utilizing the inner mesh wall to pull themselves in, a cut in the slippery panel to gain stability and increase reach, or walking sideways had an increased probability of entry, suggesting that behaviour in the funnel plays a major role in the probability of entering pot 1. My findings indicate that this design requires further modifications in order to improve the size selectivity and reduce the effect of the observed behaviours. For pot 2, the majority (85%) of undersized crabs succeeded in leaving the pot, while no legal sized crabs succeeded. Furthermore, no crab succeeded at ascending up to the main chamber, indicating that this design was highly effective at sorting out the undersized crabs at low densities (13-15 individuals).

1.Introduction

1.1 Biology of the Red King Crab

The Red King Crab *Paralithodes camtschaticus* (Tilesius, 1815) is a large crustacean inhabiting cold waters. Even though they have a crab-like body and are commonly referred to as a crab, they are not true crabs (brachyuran). They are anomuran crustaceans belonging to the family Lithodidae, which recently was found to be nested within the hermit crab family Paguridae (Noever and Glenner 2018). The Red King Crab (RKC) have a crab-like body because they have undergone carcinization and no longer require shell for protection (Noever and Glenner 2018). It is the largest out of five species belonging to the genus *Paralithodes* (Stevens 2014). The males are larger than the females, where the largest male was recorded with 227 mm carapace length (CL), and the largest female with 195 mm CL (Zaklan 2002).

True to its common name, The Red King Crab is reddish brown to burgundy coloured, with a white ventral side. As described by Stevens (2014), they have a calcified spiny exoskeleton which protect them from external threats. The head and thorax are fused into an oval shaped cephalothorax known as the carapace, with a slightly upward curved rostrum. The carapace is covered in spines, as is the top and sides of the chelae and walking legs, while the ventral side has no spines. They have a reduced abdomen with an abdominal flap which is bent under the carapace. The abdominal flap is commonly used to determine the sex of the crab. Where the adult females have an asymmetric oval shaped abdominal flap, which covers most of the body's ventral side, the adult males have a symmetrical triangular shaped abdominal flap covering a smaller proportion of the ventral side. Like other decapods, the RKC has 10 pereiopods. The first pair of pereiopods has been modified to chelipeds, where the right cheliped usually is larger than the left in adult male crabs. The second, third and fourth pairs of pereiopods are used as the apparent walking legs, while the fifth pair is reduced and hidden in the gill chamber. The fifth pair of pereiopods is used to clean and ventilate the gills. Additionally, the males use them to transfer sperm during mating, while female use them to clean and ventilate egg clutches (Stevens 2014).

Like many species with a rigid exoskeleton, the RKC must undergo moulting to grow in size. The exoskeleton itself cannot increase in size, so the crabs must replace the old exoskeleton with a larger one to continue its growth (Chang and Mykles 2011). Immediately after a moult, the new exoskeleton is soft, making the crabs vulnerable to predators, and even cannibalism (Long et al. 2012). In order to gain back the defence and locomotion provided by the exoskeleton, the recently moulted crab must take in water to expand the exoskeleton and use minerals to gradually harden it (Cameron and Wood 1985; Chang and Mykles 2011). The moulting frequency depends on maturity and season. Juvenile crabs can moult several times a year, with a decreasing frequency with age (Powell and Nickerson 1965). When the crabs become sexually mature, they will moult annually for several years (McCaughran and Powell 1977). As the crabs continue to grow in size, the largest males can eventually survive two years without moulting, while the females have to moult every year as part of the mating and reproduction cycle (McCaughran and Powell 1977).

The RKC undergo two migrations a year, a mating-moulting migration and a feeding migration (Jørgensen et al. 2005). The mating-moulting migration occurs in the late winter and early spring, where the crabs migrate to shallow waters (< 70m) to mate and breed (Powell and Reynolds 1965). During mating, the male RKC will grasp and hold a female for up to 16 days, to then mate shortly after the female moults (Powell et al. 1974). As the spawning and mating activities in the shallow water comes to an end, the crabs gradually migrate towards deeper water during autumn and winter (Jørgensen et al. 2005). Although the mature crabs migrate with the seasons, the small juvenile crabs remain in shallow waters all year (Stevens 2014). RKC can be found at depths between 5 to 460 m, depending on life stage and season, and temperatures ranging from -1.8 to 12.8 °C (Michalsen 2004; Stevens 2014). They are also quite resistant to rapid changes in water temperature between -2 °C to 14 °C (Matishov et al. 2008).

1.2 Geographical distribution

The RKC is native to the North Pacific Ocean, where it can be found in three large regional groups along coasts and in fjords (Stevens 2014). Even though the RKC is only native to the North Pacific Ocean, there is now a fourth group of RKC. This group exists in the Southern Barents Sea, along the coast of northwest Russia and Northern Norway (Jørgensen and Nilssen 2011; Stevens 2014). The RKC was introduced to the Kol'skij Zaliv region in the Barents sea in the period between 1961 and 1969 (Orlov and Ivanov 1978). A total of 2 609 large male and female crabs, 10.000 juvenile crabs and 1.5 million of Stage I zoea was released into the Barents sea during this time-period (Orlov and Ivanov 1978). This was purposely done by Russian scientist to extend the fishery range of the RKC along the Russian coast. During the 1980s, bycatch of RKC became gradually more frequent in the Norwegian coastal fisheries as single individuals or in small numbers (Kuzmin and Olsen 1994), suggesting the RKC population was successfully growing in the Barents Sea. In 1992, the bycatch in gillnet fishing increased to the hundreds in the Varanger Fjord in Norway (Kuzmin and Olsen 1994). From this point, the RKC population in the Southern Barents Sea grew rapidly and spread along the coast of Norway and Russia. Figure 1 display the extent of the RKC distribution along the Norwegian waters as of 2016. By 2019, the southward distribution along Norway has reach all the way to Tromsø (Sundet et al. 2019).

Figure 1: Distribution and quota regulated area for Red King Crab in the Barents Sea. Map modified from Lorentzen et al. (2018).

1.3 Fishery in Norway

The Red King Crab fishery in Norway is a relatively young fishery. It was established as a research fishery in 1994, and opened up for commercial harvest in 2002 (Michalsen 2004; Hjelset 2014). For the commercial fishery, there is a quota regulated area, and an area of free fishing (Sundet et al. 2019). The quota regulated zone is the area between the 26^{th} east meridian and the border between Norwegian and Russian waters, including the Porsanger fjord (Fig. 1).

The free fishing area is in the Norwegian waters east off the 26^{th} east meridian (Sundet et al. 2019). In the free fishing area, there is no quota or minimum size. According to regulation for fishing outside the regulated area, it is illegal to release living crabs or crabs capable of surviving back into the ocean (Forskrift om fangst av kongekrabbe 2004). In practice, it can be considered an extinction fishery approach, since all living RKC must be landed. The purpose of this strategy is to slow down the spread of RKC along the Norwegian coast, and to keep the density low outside the quota regulated area (Sundet et al. 2019).

The goal for the quota regulated area is to maintain a sustainable long-term RKC Fishery, while keeping the westward expansion of the RKC population to a minimum (Sundet et al. 2019). Both minimum catch size and catch quota in tonnes are applied in order to reach this goal.

The minimum legal catch size for both male and female RKC is 130mm CL in 2021 (Forskrift om utøvelse av fisket i sjøen 2005). The same year, the quotas set by the Directorate of Fisheries in Norway were of 1629 tonnes (t) male RKC, 120t female RKC and 181t injured male RKC (Anon 2021).

Over the course of the last 10 years, from 2010 to 2020, the yearly landings from the quota regulated area ranged between 930t and 2262t RKC ("Norges råfiskelag" n.d.). Meanwhile, the landings from the unregulated free fishery area were between 158t to 909t. During the last five years, from 2016 to 2020, the difference in landed quantities between the regulated and unregulated area has been greater than in the previous five years.

With the increase in market demand for live king crab, the turnover for the regulated RKC fishery has gained in the last five years. In 2020, the turnover was 354 million NOK for the regulated area and the 38 million NOK for the unregulated area, totalling at 392 million NOK. The unregulated fishery is deemed important to maintain a low RKC density in the unregulated area and reduce the spread of RKC along the coast. (Hvingel et al. 2020).

The kg price of RKC is directly related to crab size, where larger crabs are more valuable. Thus, to maximise the total value of the given quota, fishermen target the larger crabs. Like with other size selective fisheries, the average size will likely decline over time when targeting the largest individuals of a population (Conover and Munch 2002; Olsen et al. 2011). Resultingly, encountering crabs exceeding 200 mm CL has become less common over time (Stevens 2014). From 1995 to 2010 there has been a reduction in the upper 95th percentile CL of female and male RKC in three of the fjords connected to the Barents sea (Hjelset 2014). Additionally, yearly surveys in the regulated fishery area in Norway have shown a decline in average weight for legal sized male crabs (CL > 130mm) from 2000 to 2019 (Sundet et al. 2019)

1.4 Pot Fishery

Today, collapsible square pots are commonly used in the Norwegian RKC fishery. The square pots have been proven to have significantly greater catches than the conical pots previously used (Stiansen et al.

2008). Additionally, fishermen seem to prefer the collapsible square pots, as they require less storing space than the conical pots. A typical collapsible square pot consists of two metal frames connected with netting with different mesh sizes (Fig. 2). The bottom frame has negative buoyancy due to the nature of the metal, while the upper frame has positive buoyancy due to the lift created by the floaters attached to it. So, when the pot is situated on the seabed, the pot would be stretched out, creating a three-dimensional trap, which crabs are lured into using bait. In air however, the pots would collapse, making them easier to handle and stack on deck.

Figure 2: A Leif Henriksen pot (LH-pot), one of the standard collapsible pots used in the Norwegian Red King Crab Fishery.

Pots used within the regulated area must have at least four circular escape openings with a minimum diameter of 150mm, according to regulations (Forskrift om utøvelse av fisket i sjøen 2005). This is to allow undersized crabs (CL < 130mm) to escape the pots. In the unregulated area however, it is illegal to have escape openings on the pots.

An experiment performed in 2002 showed a reduction in undersized crabs caught when using pots with escape openings, compared to pots without (Salthaug and Furevik 2004). Several years later, in 2017, Jørgensen et al. (2017) performed a retention experiment to find the optimal diameter of the escape openings for the new 130mm CL minimum catch size. They found that most undersized crabs would leave the pot, when put in a bait-less pot with circular escape openings with a diameter of 150mm. Meanwhile, video recordings of pots with both escape openings and bait, have shown crabs utilizing the escape openings as both entry points and exit (Siikavuopio et al. 2018). This suggests that presence of bait is a factor affecting the retention of undersized crabs in pot fishery. Catches with up to 80% undersized crab is not unusual in the regulated area, even though the pots have escape openings (Siikavuopio et al. 2018).

Large bycatch of undersized RKC is a serious problem, both from an economical perspective and in terms of animal welfare. The work time for vessels and fishermen due to sorting and releasing the undersized crab has a direct economic impact, where larger bycatches would require more time for such activities. Another form for direct economic impact is a reduced market value for injured RKC (e.g., incomplete regrowth or missing limbs)

About 20% of the catch in the recent years have had injuries to some degree (Jørgensen et al. 2017; Siikavuopio et al. 2019). It is uncertain how many of these injuries are fishery induced, but with large bycatches it is safe to assume the handling on deck is responsible for a significant proportion. Since the pots used today are collapsible, they naturally collapse when being pulled out of the sea. This is stressful for the crabs, since they are being exposed to air and experience pressure due to the weight of the catch. Above water the crabs are prone to squeezing injuries, puncture, blunt force trauma and damage to walking legs due to handling (Zhou and Shirley 1996; Stoner 2012). Additionally, exposure to sub-zero air temperatures during winter can cause delayed mortality, reduced vigour and growth (Stevens 2014). The duration a crab can sustain sub-zero air temperatures declines with declining temperature. When investigating the relation between injuries and mortality for RKC, Stevens (1990) found injuries to be a poor indication of the survival. He suggested exposure to air or suffocation to play an important role for the survival of RKC, meaning that released pot-caught RKC may die even though it appears to be uninjured. Mortality of released undersized RKC is an obvious issue in terms of animal welfare, but it will also remove these individuals from the population. This could impact recruitment, and in turn future landings. Even though released crab with injuries do survive, they can have reduced growth due to the injuries. In the case of limb autotomy, it can take up 7 years to fully regenerate a limb as the regeneration is connected to the moulting (Edwards 1972). Individuals missing or regenerating several limbs could have reduced reproductive capabilities (Juanes and Smith 1995). Thus, injuries and mortality caused by undersized bycatch would have an indirect negative economic impact, as they reduce future harvest potential. The optimal solution for this bycatch issue would be to improve the size selective sorting on the seabed, which in turn would reduce the sorting onboard. To achieve this, it is required to design a new pot or to modify the current pot to improve its size selectivity.

1.5 Modified pot designs

This thesis is part of an ongoing project “Efficient and environmentally friendly king crab pot”, financed by Norwegian Seafood Research Fund (FHF). The project is a collaboration between Institute of Marine Research (IMR) and Nofima, aiming to develop size-selective pots with increased catch efficiency for large crabs, and efficiently sort out undersized crabs at fishing depth.

It would be easier and more cost efficient for the fishermen to apply modifications to the currently used pot designs, than to adopt a new design. Based on this, it was decided to test two different modifications to the standard collapsible pot. The two modifications represent two different strategies to achieve the overall goal; to reduce proportion of undersized crabs caught. The strategy for the first modified pot would be to physically hinder the undersized crabs from entering the pot at all, while the strategy for the second modified pot would be to stimulate undersized crabs to leave the pot at fishing depth.

The first experimental pot (Pot 1) has a selection barrier in form of a slippery panel in the entry (Fig. 4). The design principle is that a certain width of the slippery panel will hinder undersized crabs from pushing themselves over the edge of the funnel, thereby effectively preventing them from entering. If this panel is proven to be successful, the escape openings can be removed. As previously mentioned, undersized crabs have been observed to use the escape openings as entrance (Siikavuopio et al. 2018).

The use of a slippery panel for size selection has been tested on conical pots in the snow crab fishery, where it resulted in a smaller proportion of undersized crabs (Chiasson et al. 1993). Thus, the adoption of this strategy to a square pot could potentially be a success.

The strategy for the second pot (Pot 2) revolves around motivating undersized crabs to escape. It follows up on the strategy with circular escape openings, which has proven to reduce undersized bycatch (Salthaug and Furevik 2004; Jørgensen et al. 2017). Since undersized crabs may not be motivated to leave the pot when bait is present, a bottomless second chamber has been mounted beneath the standard pot (Fig. 5). Bait is placed in the second chamber, giving the crabs caught in the main chamber motivation to move to the second chamber. As the main chamber and the second chamber are connected by circular escape openings, only the undersized crabs would be able to move to the second chamber. When the pot is pulled up, the crabs in the second chamber would be left on the seabed, as this chamber is bottomless. Additionally, by making the escape openings inaccessible from outside the pot, crabs would not be able to enter the pot via the escape openings.

Testing these modified pots can be done in several ways, but in order to alter the modifications for improved size selectivity in the future, it is essential to observe the crabs' behaviour in relation to the modifications. For the pot with size selection barrier, behaviours employed by the crabs to surpass the barrier could be identified. While for the two-chamber pot, observations are necessary in order to record if crabs moved both directions through the escape openings. My thesis work is a set of laboratory-controlled studies, where I investigate the crab's entry and escape behaviour in relation to two modified pots.

1.6 Red King Crab behaviour in relation to pots

When using passive baited fishing gear, such as pots, the behaviour of the target species plays a major role for the catch efficiency of the gear. The majority of RKC encountering a pot would do so from a downstream position (Zhou and Shirley 1997b; Stiansen et al. 2010), whereby as they follow the odour plume in order to locate food. Further, the orientation of a square pot in relation to the current has an effect on entry rate of RKC following an odour trail (Miller 1990). RKC approaching a square pot upstream are more likely to enter the pot if the funnel is parallel to the current than if funnel is perpendicular to the current (Stiansen et al. 2010). However, Stiansen et al. (2010) observed a more flexible search strategy for the crabs encountering the pot by moving across the current, than for those that encountered the pot by moving up-current. The crabs following the odour plume did not deviate much from the odour plume in their search. Similarly, Zhou and Shirley (1997b) found that when encountering the pot, 78.3% of RKC searched less than a 90° angle from the pot centre before either entering or leaving the pot. The crabs successfully entering the pot spent more time searching and for a significantly larger angle than those that did not enter.

Although chemosensory is vital for locating food, other stimuli can assist the RKC in this process. For instance, the RKC can registrate sounds emitted when individuals of the same species are feeding. These sounds can stimulate to increased activity, and even cause them to move towards the source of the sound (Tolstoganova 2002). This is beneficial to pot fishery, where RKC feeding in a pot can contribute to stimulate more RKC to enter the pot.

Understanding the RKC behaviour in relation to pots can be very useful for modifying pots or testing different pot designs. As mentioned before, square collapsible pots have significantly greater catches than conical pots in Norway (Stiansen et al. 2008). By investigating the RKC behaviour in relation to square pots and conical pots, Stiansen et al. (2010) found that the probability of entering a square pot was 20 times higher than for a conical pot when vertical search was initiated. Suggesting the vertical search is the cause for difference in catch efficiency. The entrance of a conical pot is above the bait, so they concluded the difference in catch was due to the crab not finding the entrance.

In a lab experiment performed with a square pot, Zhou and Shirley (1997b) found that 52.9% of the crabs entered the pot anteriorly, while 41.2% entered sideways. The majority of the crabs entering sideways entered with their right-hand side first. Entry duration, from when the first leg was inserted into the funnel to when the crab was captured, was between 0.22 and 3.02 min (average < 1 min). Similarly, in situ, Stiansen et al. (2010) observed four crabs entering the pot in < 30 sec, while 55% of the crabs captured had entered within 90sec of initiating vertical search.

1.7 Aims and objectives

This study was initiated to better understand how RKC interact with the modifications made to the standard collapsible square pot to improve it size selectiveness. The aim was to examine the behaviour of RKC attempting to enter a collapsible square pot (control), both successfully and unsuccessfully, and to compare this behaviour with that of crabs attempting to enter a square pot modified with a slippery panel in the funnels (Pot 1). Additionally, escape and re-entry behaviour from the main chamber to the baited bottom chamber was studied for the two-chamber design (Pot 2). The first pot modification (Pot 1) was designed to control entry, while the second (Pot 2) two was designed to control escape.

Objectives of this study:

1. To determine the effectiveness of a slippery panel as a size selective barrier.

I predicted that the slippery panel would function as a size selective barrier, as I expect the crab's ability to force the panels is restricted by their carapace width and length of walking legs. My prediction is based off the results from testing a plastic panel on conical traps in snow crab fishery (Chiasson et al. 1993) and observations from a pilot study performed in relation to this study.

2. To investigate if the addition of a slippery panel alters the behaviour of RKC in the funnel of a pot.

I expect the addition of a slippery panel to affect the entry behaviour in terms of preventing grip and changing the odour plume. Since most RKC enter the pot relatively quickly after locating the entrance (Zhou and Shirley 1997b; Stiansen et al. 2010), I expect similar observations for the control trials. But with the addition of slippery unperforated panel in the funnel I predict an increase in entry duration for the experimental pot.

3. To uncover behavioural characteristics/strategies (if any) which allow some crabs to pass the slippery panel while others are unable to pass

    a. Determine the effect of certain behavioural units on entry rate for all crabs, undersized crabs and legal sized crabs

I expect to find some behavioural characteristics that provide an advantage in overcoming the selection barrier. Such behaviour could be gripping the funnel edge, use of inner mesh wall to pull the body across the panel, carapace orientation, crab position in funnel. These predictions are based on own observations.

4. To investigate the effectiveness of the second chamber in the two-chamber pot.

    a. Do crabs descend into the bottom chamber?
    b. Are crabs able to ascend back up into the upper chamber?
    c. What size are the crabs descending?
    d. Do the legal sized crabs (CL > 130mm) attempt to descend or block the escape openings?

I predict the two-chamber pot will be highly efficient in allowing undersized crabs to escape at low densities. This is based on findings for a two-chamber solution with a different design (Siikavuopio et al. 2018), where 47% of undersized crabs caught were found in the secondary chamber. Additionally, during the pilot for this study, undersized crabs were observed moving through the escape openings, in both directions.

2. Materials and Methods

2.1 Pot designs

Three different pots were used in this study, one control pot and two experimental pots (Pot 1 and Pot 2). The extensive behavioural analysis was performed on observations from a paired setup with the control pot and Pot 1. The control was a Leif Henriksen pot (LH-pot) without modifications (Fig. 2), which is a common square collapsible pot for RKC fisheries in Norway. The pot has an upper and a lower square metal frame measuring 150x150cm, and height of 90cm when fully stretched out (Fig. 3). The upper frame has positive buoyancy due to 14 floaters attached to it, with 550g lift each. The pot has two entrances on opposite sides, with a funnel running in an upward angle. The funnel functions as a tapering ramp up to a 60cm wide and 27cm high opening close to centre of the pot. The two experimental pots were modified LH-pots. Where pot 1 will be referred to as the slippery-panel pot due to its only modification, the addition of a slippery fabric (Grey PVC 600g/m2) in the upper part of the funnel (Fig. 4). Three slippery panels were added to each funnel, in a manner which covered the entire surface of the upper funnel, except for the ceiling. The width of the slippery panel was initially 25cm, then changed to 30cm and finally 50cm.

For pot 2, a secondary chamber was attached under the LH-pot. The upper chamber remained identical to the chamber in an LH-pot, while the second chamber measured 37cm in height and had no floor. The only connection between the upper and lower chamber were 8 circular stainless-steel escape openings with a diameter of 150mm each, situated close to centre of the pot (Fig. 5). The pot was modified with additional 6 floaters (800g lift each) to compensate for the added weight from the second chamber and the additional aluminium frame.

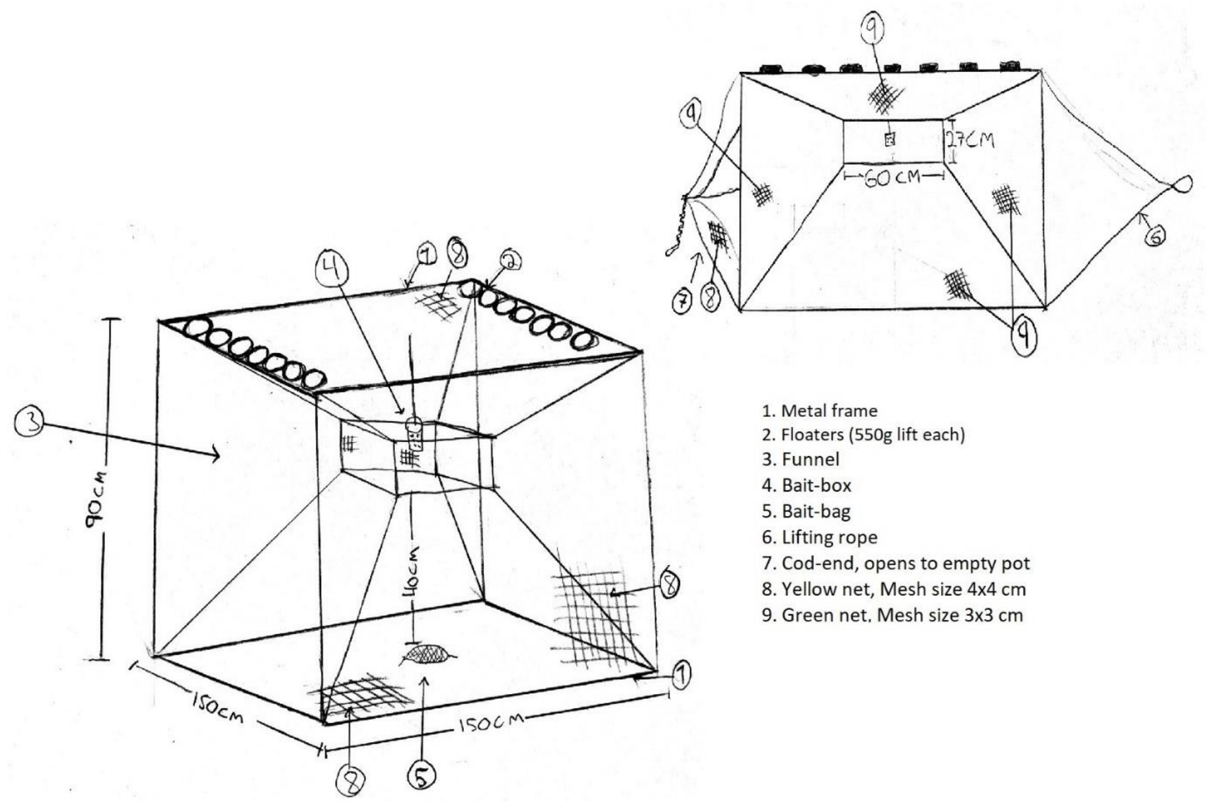

Figure 3: Standard LH-pot with measurements and descriptions

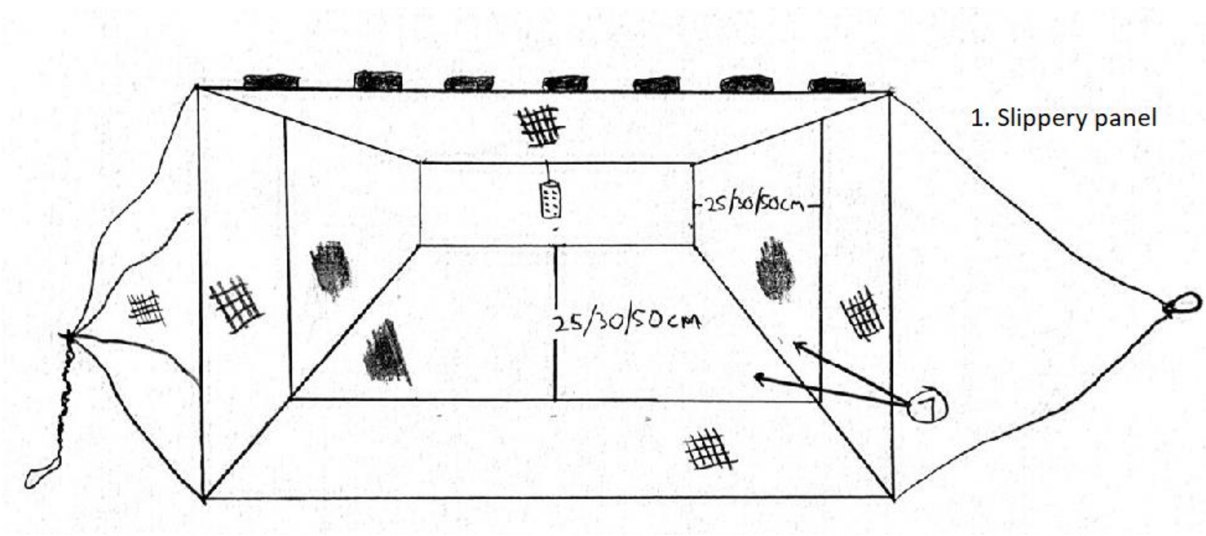

Figure 4: Modified LH-pot, referred to as slippery-panel pot. The pot was used with a slippery panel width of 25, 30, and 50 cm. Besides the slippery panel, all measurements are the same as for the standard LH-pot.

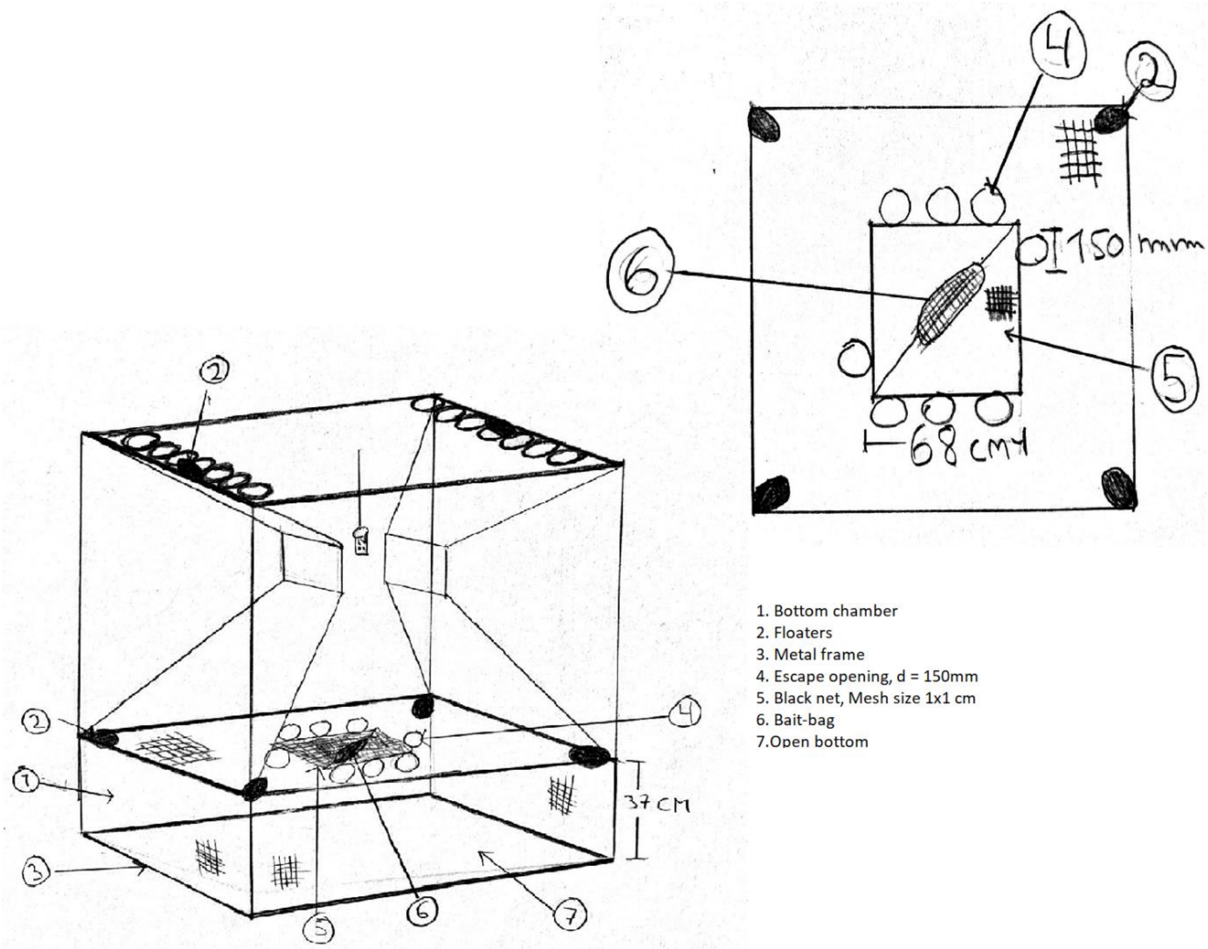

Figure 5: Modified LH-pot, referred to as two-chamber pot. The modifications add an additional chamber under the LH-pot, with an additional metal frame. Illustrated changes are done to the bottom of the upper chamber, the bottom chamber is bottomless. Besides these modifications, all measurements are the same as for the standard LH-pot

2.1.1 Bait

Atlantic herring (*Clupea harengus*) was used as bait in all the pot designs as it is the most commonly used bait in the RKC fisheries in Norway. The control and slippery-panel pot were baited the same way, with three herring cut in two, one herring in the cylindrical bait container hanging at the same level of the entrances, and two herring in the meshed bait bag situated at the centre of the pot floor. Similarly, the two-chamber pot had one herring in the hanging bait container, and two in the bait bag. However, the bait bag was situated in the ceiling of the bottom chamber. It was placed there to lure the small crabs in the upper chamber down to the lower chamber. To hinder the crabs in the upper chamber to reach the bait bag, a fine mesh net (1 x 1 cm) was mounted in the ceiling of the bottom chamber, above the bait bag (Fig. 5).

2.2 Video recording

Three camera setups were used in the laboratory experiments: i) a GoPro Hero 4 in a standard underwater housing, connected to a power outlet with a car battery as backup. This setup was limited by storage capacity on the micro-SD card. Setup ii) and iii) were identical and wireless, consisting of a GoPro Hero 5 and a power bank in a Benthic 3 underwater housing kit from Group B Distribution Inc (Appendix 4). The power banks abled recording for 15-18 hours, slightly shorter than the 19–20-hour duration of the individual experimental round. Two cameras were used for the control and slippery-panel pots, one in each funnel (camera setup I and ii). These systems were mounted to the tank wall, under water. For the two-chamber pot, the remaining wireless camera system (iii) was mounted submerged inside the upper chamber.

2.3 The experiments

Two laboratory experiments were conducted, an entry experiment for the slippery-panel pot and an escape experiment for the two-chamber pot. The experiments were run in two experimental periods, the first occurred between 25/08/2020 and 06/09/2020, the second between 26/09/2020 and 01/10/2020 The entry and escape experiments were run in parallel during the first period, while only entry experiment was conducted in the later period.

2.3.1 Experiment 25/08 – 05/09

The first experiment consisted of a series replicate tests with 6 groups of male *Paralithodes camtschaticus*, were each group had 15 individuals. Due to the small size of the available crabs, one large crab (CL > 12.8cm) was assigned to each group, while the rest were picked randomly from a large containment tank. The largest crab in each group was marked with the number 15, while the rest were marked with numbers 1 to 14. Marking was done with white correction fluid on the gastric region of carapace (Fig. 6). All crabs were measured for Carapace Length (CL), Carapace Width (CW) and Length of right second walking leg (LL) (Fig. 9, Appendix 1). If right second walking leg was missing, the left second walking leg was measured instead, which was the case for three individuals (Appendix 1). CL was measured from the right eye-socket to the posterior part of carapace (Fig. 6). CW was measured on the widest part of carapace (Fig. 7). The second walking leg was measured from body to tip, carefully extended without use of excessive force (Fig. 8). All measurements were made to the nearest mm using a calliper.

Figure 6: Carapace length was measured from eye socket to posterior part of carapace. ID marked in white.

Figure 7: Carapace width was measured on the widest part of carapace.

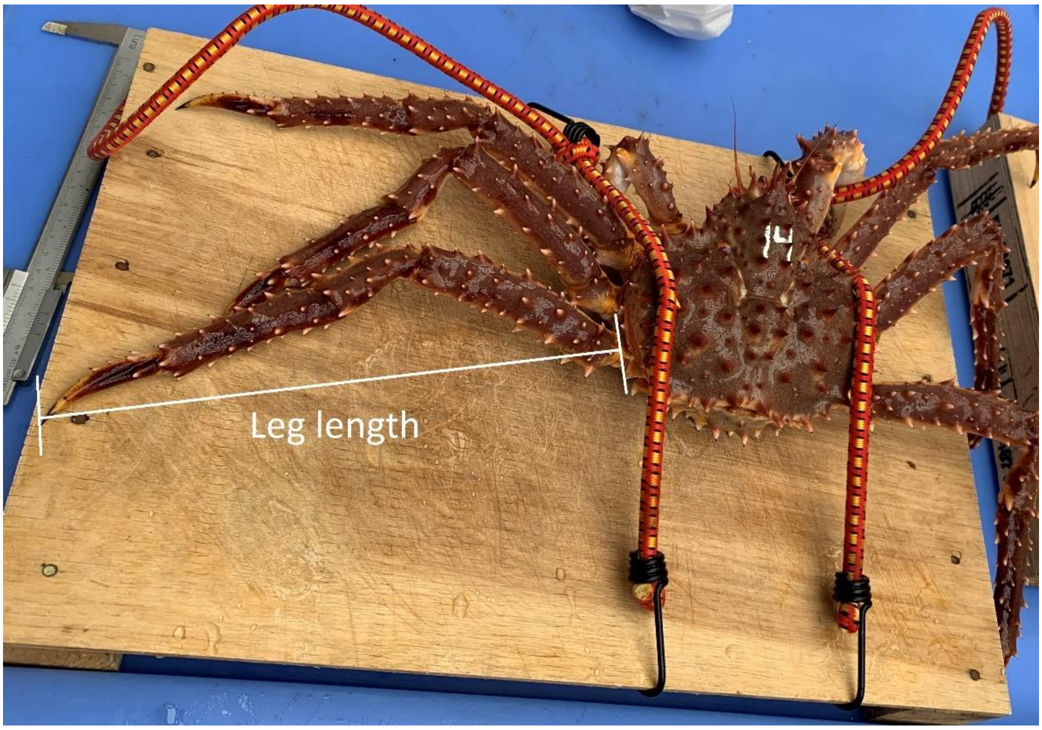

Figure 8: Leg length was measured from the body to the tip of the leg, carefully extended without use of excessive force (more extended than as demonstrated in the picture). The second right walking leg was measured, if second right walking leg was not present, the second left was measured. Image shows the third left walking leg for demonstration purpose only.

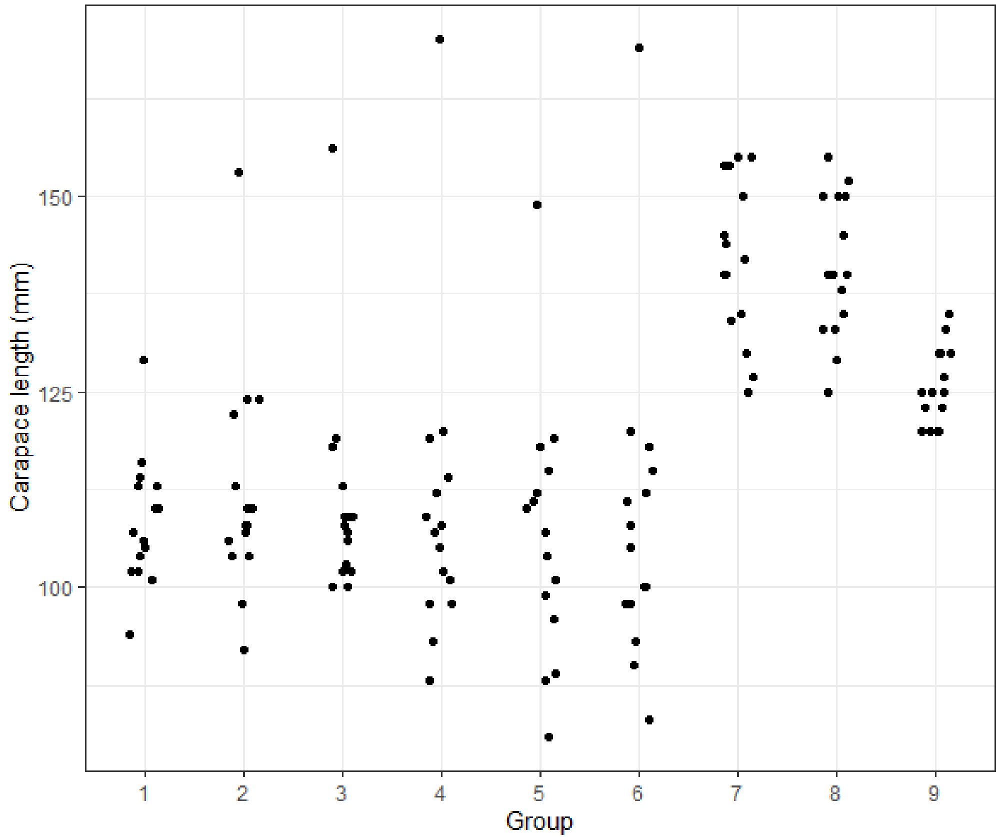

Figure 9: Overview of Carapace length (mm) for all the crabs included in experiment. Measurements are shown separately for each of the 9 experimental groups. Each point represents an individual crab.

All crabs were starved for at least one week prior to experiment, to motivate them to search for food. At least 3 days before being used in the experiment, crabs were divided into isolated groups, in which they were kept for the duration of the experiment. This was done to allow the crabs to get used to each other and create a hierarchy before being exposed to the pot study.

Individuals 3 and 14 in group 3 moulted during the experimental period (04/09/2020) (Appendix 1). These individuals were removed from the experiment and did not participate in the two-chamber trial for group 3.

2.3.1.1 Water tanks

Two tanks were used for the experiment, while several tanks were used as waiting tanks for the groups awaiting their turn in the experiment. All tanks had constant water circulation with natural sea water being pumped in from 50 m depth in the fjord outside the facility. The mean temperature was 9.9 °C, ranging from 9.2 °C to 10.2 °C over the course of the experiment. The largest tank available was used for the paired setup with control and slippery-panel pot. It was a circular tank measuring 5 meter in diameter and deep enough to fully submerge the pots (>1m). The seawater entered the tank (200 l/min) through a vertical pipe close to the tank wall. Perforations along the entire length on one side of the pipe caused a circular current in the tank. The water outlet was in the centre of the tank (Fig. 10). The control or slippery-panel pot was positioned along the tank wall, on the opposite side of the water inlet. Observations from a pilot study suggested a higher number of attempts to enter when pot was situated in contact with the tank wall, as opposed to in the middle of the tank. Thus, placing pots next to the wall should result in more behavioural data in the funnel. The pots were positioned so that both funnels were accessible. The tank was covered by a tarpaulin hanging from the ceiling during soak time and artificial white light (45-80 LUX at water surface) was provided by a hanging LED lamp for the full duration of experiment.

The two-chamber pot was tested in a smaller square tank, measuring 2x2 m with a depth of 1m, with similar water circulation system to the larger tank. Water entered (60 l/min) via a vertical pipe along the side and exited via a drain in centre of the bottom. The two-chamber pot was not fully submerged, were the upper 30cm of the pot was in the air. As it was not possible to fully submerge the pot, it was supported by a rope attached to the ceiling. This caused the pot to behave as if it was fully submerged and suspended by its float. At the start of the experiment, the crabs were placed in the top chamber of the pot, so that they would be fully submerged unless they climbed up to the roof of the pot. This tank was not covered and did not have artificial light for groups 1 and 2. As the lab had transparent roof, the light conditions inside the tank was the same as outdoor. So, for groups 1 and 2, the light faded towards the night, with 5 hours of complete darkness before the light intensity increased with sunrise. For groups 3-6, artificial white light was added due to no visibility for the recordings during night. A LED work light with adjustable intensity was placed over the tank, where the intensity was set to match the light conditions at the large circular tank.

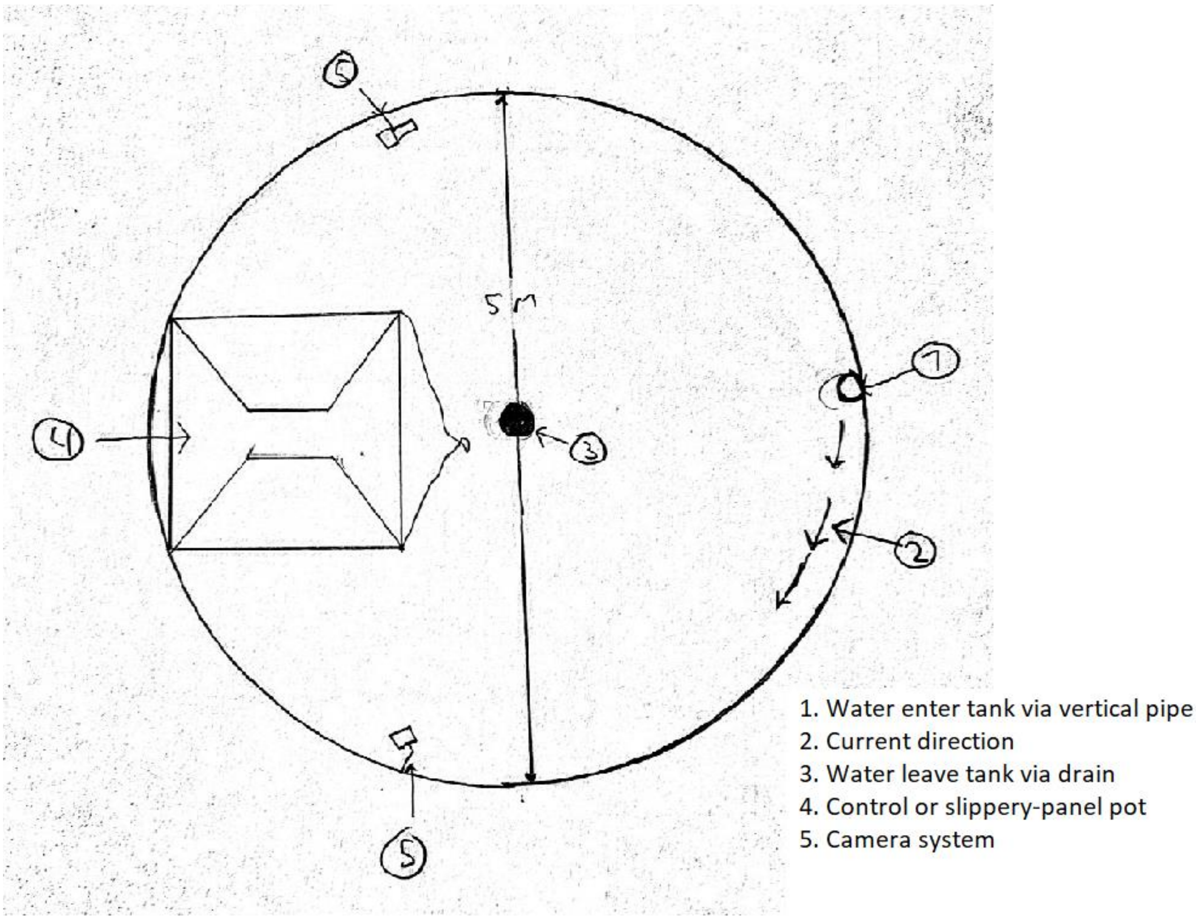

Figure 10: Circular water tank used for control and slippery-panel pot

2.3.1.2 Study design

The initial study design was changed over the experimental period. The initial plan was to expose all 6 groups to a 25 cm wide slippery panel. This panel width was chosen based on observations from a previous pilot study. However, results from the 1st, 2nd and 3rd group in this study showed that both a 25 and 30 cm panel did not prohibit the smaller crabs from entering. Thus, the panel was extended to 50cm (see below). To mitigate the effects of naïve crabs versus crabs who have previously encountered pots, the groups were exposed to the different pot designs (control and slippery-panel) in a specific order. The order is only relevant for the control and slippery-panel pot, as the crab's behaviour in these two pots were compared. Groups 1-3 were exposed to the slippery-panel pot before the control pot, while groups 4-6 were exposed to the control pot first (Table 1).

After observing a very high successful entry rates for a low number of attempts for groups 1 and 2, the slippery panel was replaced by a 30 cm wide panel for group 3. Footage from group 3 indicated that a width of 30 cm was still too small, as crabs in groups 1-3 were frequently observed using their walking legs to push themselves over the edge, with contact just below the slippery panel. Based on these observations, a Pearson product-moment correlation coefficient was computed to determine the relationship between the Carapace length (CL)(mm) and leg length + Carapace width (LL + CW)(mm), which were found to be highly correlated (r= 0.97, n = 135, p = 2.2e -16; Fig 11). Thus, the sum of carapace width and length of one leg was used as indication for finding a suitable slippery panel width for the remaining trials.

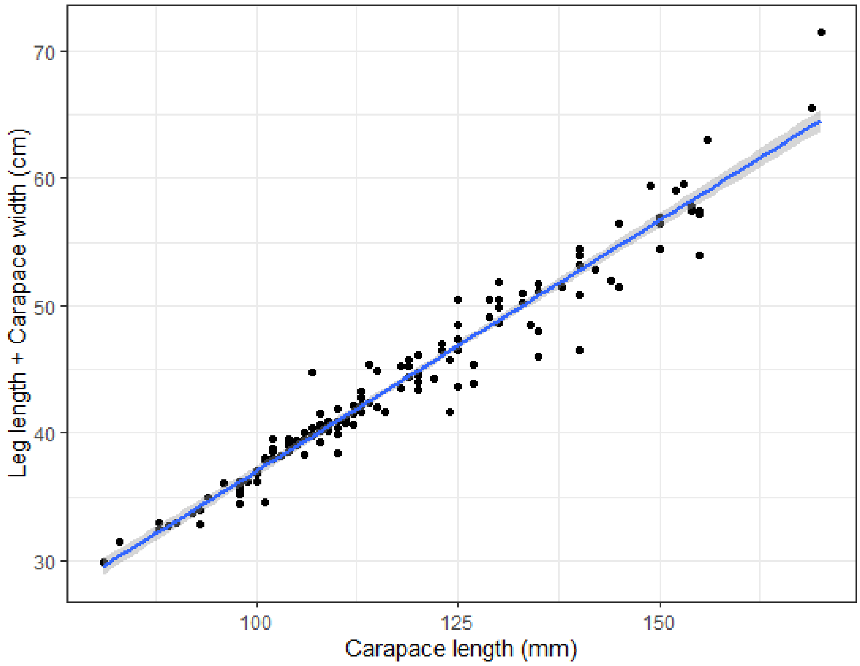

Figure 11: The relationship between Carapace length (mm) and leg length + Carapace width (cm) was found to be highly correlated using a Pearson's product-moment test (r = 0.97, n = 135, p = 2.2e-16). Leg length was measured as the full length of the Right second walking leg, If the Right walking leg was injured, the left one was measured. Grey area represents 95% Confidence interval for best fitted line.

At the end of the first experimental period, groups 4-6 were exposed to a slippery panel of 50 cm width (Table 1). All 6 groups went through three rounds, one for each pot design. In each round, the crabs were exposed to the pot overnight, for 19-20hours.

Table 1: Group: numbers represent the 9 groups of 15 crabs. The rest of the columns represent the order in which each group were exposed to the different pot designs. Control: LH-pot without modifications. Slippery-panel: Pot with the slippery panel modification, the width of the panel is given in brackets. Two-Chamber: Pot modified with an additional bottomless chamber, situated beneath the initial chamber. Groups 7-9 were not exposed to the Two-Chamber design.

Group	Exposure		
	Control	Slippery-panel	Two-chamber
First exp. period:			
1	3rd	1st (25 cm)	2nd
2	2nd	1st (25 cm)	3rd
3	2nd	1st (30 cm)	3rd
4	1st	3rd (50 cm)	2nd
5	1st	3rd (50 cm)	2nd
6	1st	3rd (50 cm)	2nd
Second exp. period:			
7	2nd	1st (50cm)	
8	2nd	1st (50cm)	
9	2nd	1st (50cm)	

2.3.2 Experiment 26/09 – 01/10

The second experimental period was an extension of the control and slippery panel part of the first experiment. Due to the changes of panel width in the initial experiment, an extension was deemed necessary to acquire sufficient behavioural data with a slippery panel width of 50 cm. As the slippery panel trials are paired with control trials, the new groups of crabs had to undergo both segments.

The crabs for the latter experiment were caught by the R/V Kristine Bonnevie in the Porsanger fjord 19/09/2020. A total of 45 crabs were acquired and marked with numbers from 1 to 45 in the same manner as in the first experiment. From these 45 crabs, three groups of 15 individuals were created, and isolated following the same procedure as in the first experimental period (see above). The groups were exposed to the slippery-panel pot first, then the control pot. The opposite order of exposure compared to that of groups 4-6 (Table 1). This experiment was performed in the same way as the first experiment, apart from not including a two-chamber segment.

2.4 Video analysis

Video recordings from the two experimental pots (slippery-panel pot and two-chamber pot) were processed and analysed separately. As the control pot was paired with the slippery-panel pot, the video from these rounds were processed and analysed together.

2.4.1 Slippery-panel pot

From groups 1 to 9, a total of 520 hours of video was recorded; 260 hours for the slippery-panel pot, and 260 hours for the control pot. Two camera systems were used for both pot designs, so 260 hours of video equals 130 hours of soak time. As this study was aiming at studying behaviour in the funnel, only the segments of the video which were considered as an "Attempt" (Table 2) were included in the analysis.

2.4.1.1 Preliminary observations

Preliminary observations of video from the control and slippery-panel pot were done to identify behavioural units relevant to the hypothesis being tested (see Ethogram; Table 2). These behavioural units were recorded as either a state or an event. A state is a behavioural pattern with a relative long duration (Martin and Bateson 2007). Start and end point of the states were noted, and the duration measured in seconds. All states within the behavioural categories are mutually exclusive. For example, one category used in this study was "Carapace orientation". Contrastingly to a state, event is a behavioural pattern with a relative short duration (Martin and Bateson 2007).

Table 2: Ethogram of Red king crab behaviour in relation to pots

Behaviour	Type	Description
Attempt	State	
Start		A crab is attempting to enter the pot when its entire carapace has passed the bottom metal frame and is fully in the funnel.
End		The attempt can end successfully or not successfully. It ends successfully if the carapace fully passes the inner edge of the funnel (Fig. 14). It ends unsuccessfully when the carapace is over the bottom metal frame and no longer fully inside the funnel. However, if the crab resumes the attempt within 30 sec, it will count as one attempt, not two.
Carapace orientation		Carapace orientation with inner funnel edge as reference point. (Fig. 12) Edge used as reference point depends on crab position (Panel A, B or C).
CFWD	State	Carapace facing forward
COBLQ	State	Carapace facing obliquely, either side
CSIDE	State	Carapace facing sideways, either side
CBCK	State	Carapace facing backwards
Crab position		Crab position in funnel (Fig. 13)
CPA	State	Crab only in in contact with panel A
CPAB	State	Crab only in contact with panel A and B
CPB	State	Crab only in contact with panel B
CPBC	State	Crab only in contact with panel B and C
CPC	State	Crab only in contact with panel C
IMW	Event	Crab is in contact with inner mesh wall between funnels (roof not included) (Fig. 14)
GRIP	Event	Crab grips inner edge of funnel with claw
MORE	FALSE/TRUE	More than one crab attempting to enter pot
REACH	Event	Crab successfully reaches the inner edge of slippery panel, with foot or claw (event)
CUT	Event	Crab utilises CUT in slippery panel (Relevant for groups 4-9, 50cm) (Fig. 15)
CURRENT	FALSE/TRUE	Crab moving against current

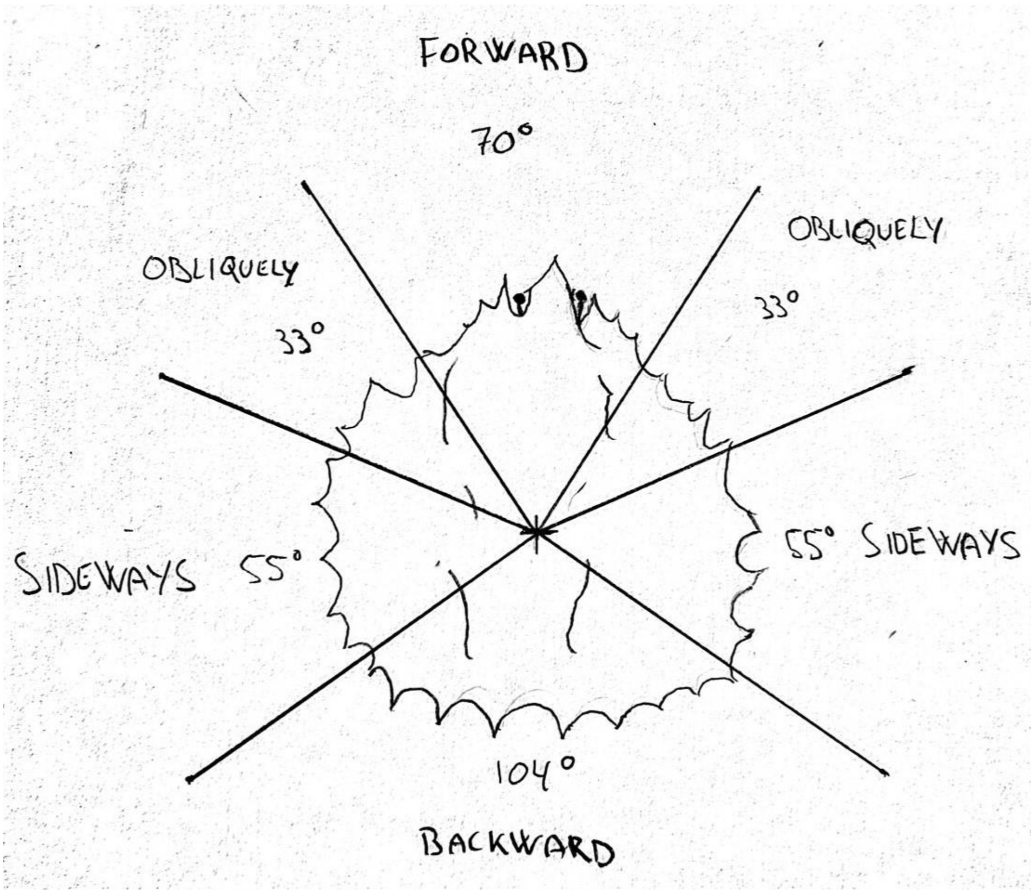

Figure 12: Carapace orientation with inner funnel edge as reference point. Inner funnel edge used as reference point depends on crab position (Panel A, B or C).

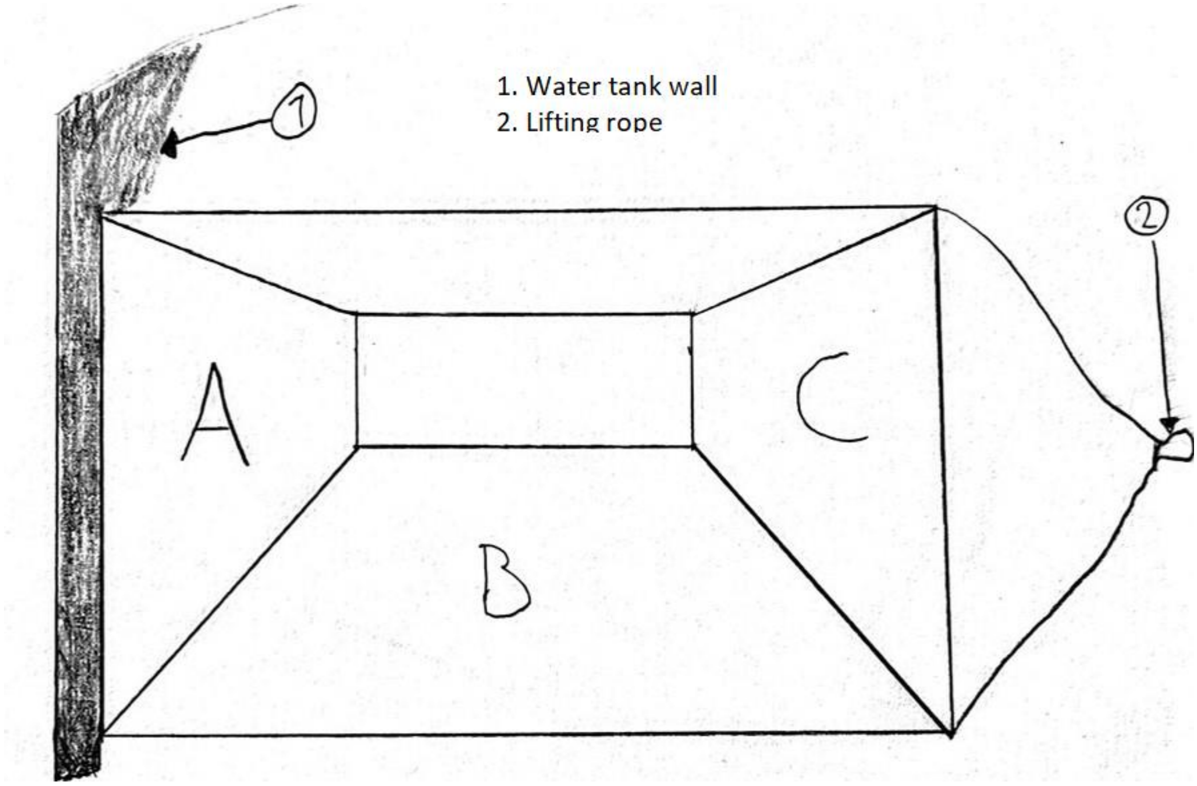

Figure 13: Panel definitions for control and slippery-panel pots. Panel A is the panel closest to the wall of the water tank. Panel B is the middle panel. Panel C is the panel closest to the Lifting rope.

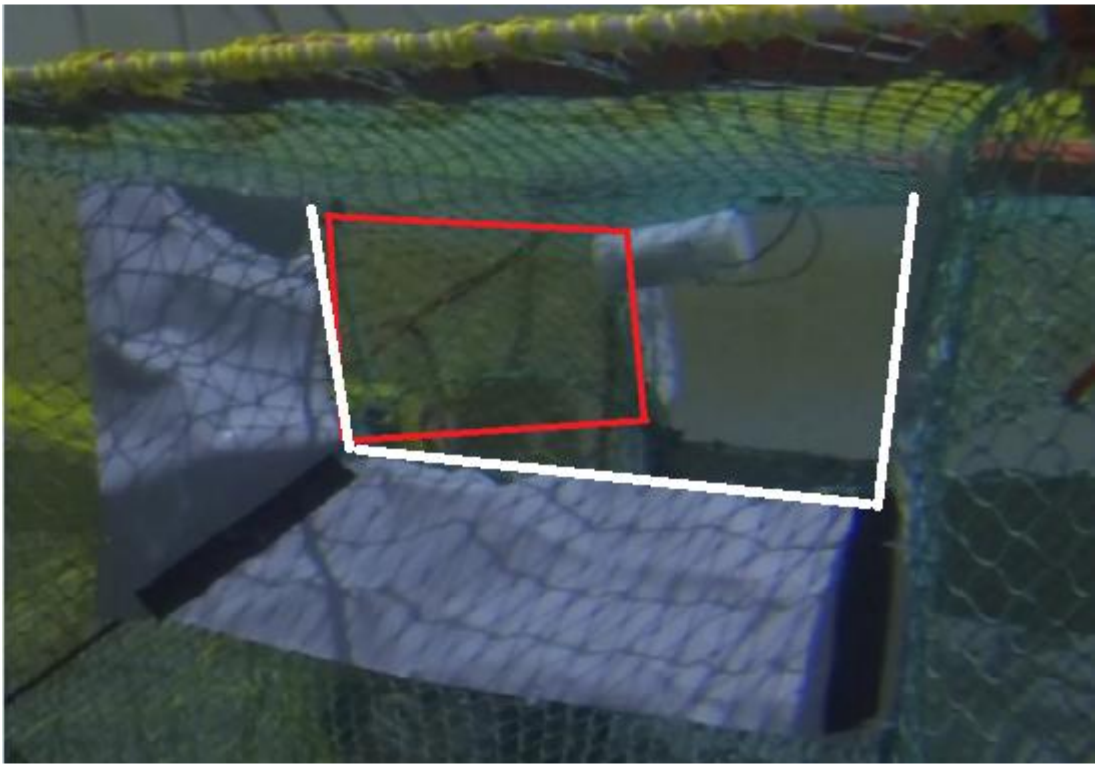

Figure 14: There is an inner mesh wall (Marked red) between the two funnels, on both sides of the entrance. Inner funnel edge is marked white.

Figure 15: Location of cut in panel A in the 50cm slippery panel. The slit is a result of patching due to limited material when changing from 30 cm to 50 cm slippery panel.

2.4.1.2. Behavioural sampling

For each attempt (as defined in Table 2), data sampling was performed following the created ethogram. A focal method was employed, recording all instances of behaviour for one individual over a time period (Martin and Bateson 2007). The period was defined by the start and end for each attempt. This is a continuous method of behaviour sampling, providing true frequencies and durations, which was necessary with the highly varying attempt durations and low frequency of events. The focal method was suitable since it follows a single individual for its full duration in the funnel, regardless of other individuals in the observation window. States and events were recorded using the event logger "Behavioral Observation Research Interactive Software" (BORIS) (Friard and Gamba 2016).

In order to provide a measure of the within-observer reliability, 10 entry attempts were selected at random for re-sampling. The original sample and the resample were used to compute a Cohen's kappa coefficient via the built-in reliability function in BORIS. The kappa coefficient describes to what extent an observer obtains consistent results when measuring the same thing on different occasions. It ranges from 0 to 1, where a value of 0 indicate no agreement between observations and a value of 1 indicate perfect agreement (Warrens 2015). For this study, the average kappa coefficient was 0.68, which is considered as substantial agreement.

2.4.1.3. Slippery panel efficiency

The purpose of the slippery panel in the modified pot was to keep the smallest individuals from entering the pot. In general use, the catch efficiency would reflect the efficiency of the slippery-panel pot relative to the control pot. But in order to truly investigate the efficiency of the slippery panel, it is necessary to also include the failed entry attempts. Thus, ID number, size, attempt number and success or fail was recorded for each attempt (as defined in Table 2). This method allowed me to exclude the crabs that did not attempt to enter, from the analysis, and include those that failed to enter.

2.4.2 Two-chamber pot

A total of ca. 70 hours of video from groups 2-6 in the two-chamber segment was used for simple observations. Group 1 was used as a pilot, since the pot design was modified between the original pilot experiment and the main experiment. ID number and CL was noted for crabs which descended from the upper chamber to the bottom chamber. If a crab successfully ascended from the bottom chamber to the upper chamber, its ID number was noted. If a crab moved between the chambers several times, the number of descents and ascents were noted. Ca. 5 hours of video from group 2 was disregarded due to lack of visibility, however, the crabs found in the bottom chamber after this period were noted.

2.5 Statistical methods

I conducted all statistical analysis in R version 4.0.5, aided by R studio version 1.3.1073 (R Core Team 2019; RStudio Team 2020)

2.5.1 Catch efficiency

For estimation of entry rate and proportion of successful attempts, I divided the crabs into two size groups, small crabs (CL < 130mm) and large crabs (CL ≥ 130mm). The groups were separated by CL of ≥ 130mm, since it is the legal catch size in Norway. Entry rate and proportion of successful attempts were estimated as follows:

$$Entry\ rate\ (individuals) = \frac{Number\ of\ crabs\ which\ entered}{Number\ of\ crabs\ which\ attempted\ to\ enter}$$

$$Proportion\ of\ successful\ attempts \frac{Number\ of\ successful\ attempts}{Number\ of\ attemps}$$

2.5.2 Behaviour data for control and 50cm slippery-panel pot

For the behavioural data, I used the median CL (CL = 120mm) to divide the crabs in two groups, small (CL ≤ 120mm) and large crabs (CL > 120mm). I did this to get approximately similar number of crabs in both groups for analysis. 130 mm as separator would have resulted in very uneven group size.

2.5.3 Statistical tests

Parametric and nonparametric tests were used where appropriate.

A Welch's t-test was performed to compare the mean CL (mm) between the crabs which successfully entered the 50cm slippery-panel pot, and those that failed.

Pearson's Chi-squared test was used to investigate the relationship between entry success and pot type (Control vs slippery-panel pot (25cm, 30cm and 50cm) for all undersized crabs in groups 1-9.

A Fisher's Exact Test was used to investigate the relationship between entry success and pot type (Control, 50cm slippery-panel pot) for all legal sized crabs in groups 4-9. It was additionally used to examine the relationship between carapace orientation, crab position in funnel and successful/failed entry attempt.

A paired t-test was conducted to compare the mean attempt duration (s) between crabs which successfully entered the 50cm slippery-panel pot and the control pot.

A paired Wilcoxon signed rank test was used to confirm a difference in attempt (s) between crabs which successfully entered the 50cm slippery-panel pot and the control pot.

2.5.4 Models

Two separate binomial generalised linear models (GLM) were produced to predict a selection curve for the 50cm slippery-panel pot. One model was fitted to predict the probability of entry as a function of CL (mod 1). With successful entry as logical response variable (1 = success, 0 = fail), CL (mm) as continuous predictor and a logic link function.

(1) $$GLM(Successful\ entry \sim Carapce\ length(mm), family = binomial)$$

The other model was fitted to predict probability of REACH as a function of CL (mod 2). REACH is defined as the crab successfully reaching the inner edge of slippery panel, with foot or claw (Table 2).

(3) $$GLM(REACH \sim Carapce\ length(mm), family = binomial)$$

A third binomial GLM was produced to predict a selection curve for the escape chamber of the Two-chamber pot. It was fitted to predict the probability of descension to the escape chamber as a function of CL (mm).

(3) $$GLM(descension \sim Carapce\ length(mm), family = binomial)$$

McFadden´s pseudo R^2 was computed to indicate the models predicting power. It ranges from 0 to 1, where close to 1 means greater predicting power.

3. Results

The focus of this study was the entry of the pot, and therefore the camera view did not cover the entire tank (Appendix 5, Appendix 6). However, observations of crabs, after being released into the experimental tank, showed that the crabs moved seemingly random around before they started to move along the tank wall. The crabs tended to be relatively active in moving along the tank wall, with a few breaks of no movement after several hours. Occasionally, a couple of crabs aggregated in the field of view as they were walking into the wall, more often than not along the upstream side of the pot.

Most attempts at entering the slippery-panel pot and the control pot occurred in the entrance upstream to the bait bag (83.7% (n = 258) and 77.4% (n = 142) respectively). Here, all attempts include multiple observations from numerous individuals.

3.1 Catch efficiency

3.1.1 Entry rate

Not all crabs included in the experiment attempted to enter the pots. Only 60% of groups 1-2 attempted to enter the 25cm slippery-panel pot, 80 % of group 3 attempted to enter the 30cm slippery-panel pot, and 65.5% of groups 4-9 attempted to enter the 50cm slippery-panel pot. While for the control, the proportions were 70%, 73.3% and 78.9% respectively. Of crabs attempting to enter the pot, a decreasing entry rate was observed for undersized crabs (CL < 130mm) with an increasing width of selection panel (Table 3).

When comparing entry success for undersized crabs (CL < 130mm) between the experimental pots and corresponding control pots, no significant difference was found for the 25cm slippery-panel pot (Chi Square test, $p = 0.32$) and the 30cm slippery-panel pot (Chi Square test, $p = 0.45$). However, a significant difference was found for the 50cm slippery-panel pot (Chi square test, $p < 0.001$), where the undersized crabs were more likely to successfully enter the control pot than the experimental pot. For the legal sized crabs (CL ≥ 130mm), there was no significant difference in entry success between the control pot and the 50cm slippery-panel pot (Fisher's Exact, $p = 0.067$). For the 25cm and 30cm slippery-panel pots, there were not sufficient legal sized crabs in the groups (groups 1-3; Table 3) to determine an effect of these selection barriers. Only two larger crabs attempted to enter the 25cm and 30cm slippery-panel pots, and both did so successfully. Altogether, the entry rate was greater for legal sized crab (0.65, n = 20) than for undersized crabs (0.36, n = 39) on the 50cm slippery-panel pot (Table 3). Given that there was no clear difference in entry rate between the experimental pots with 25cm and 30cm panel and the control pots, only data from the 50cm slippery-panel pot was used to produce the following results.

Table 3: Groups are joined by the size of slippery panel in pot 1. Entry rate (individuals): number of crabs which entered / number of crabs which attempted to enter. Proportion of Successful attempts: number of successful attempts / number of attempts. Two crabs entered the pot twice; 109 entered the control twice, 415 entered the 50cm experimental pot twice.

Group	Pot	Crabs Attempting (individuals)	Total # of Attempts	Crabs Entering successfully	Entry rate (individuals)		Proportion of Successful attempts	
					CL < 130	CL ≥ 130	CL < 130	CL ≥ 130
1-2	25cm panel	18	25	15	0.82 (n=17)	1 (n=1)	0.58	1
3	30 cm panel	12	26	9	0.73 (n=11)	1 (n=1)	0.35	0.33
4-9	50 cm panel	59	207	27	0.36 (n=39)	0.65 (n=20)	0.096	0.23
1-2	Control	21	27	19	0.95 (n=21)	NA (n=0)	0.78	NA
3	Control	11	20	10	0.90 (n=10)	1 (n=1)	0.47	1
4-9	Control	71	95	63	0.88 (n=41)	0.9 (n=30)	0.75	0.57

3.1.2 Size selectivity

The mean CL (mm) was significantly larger for the crabs that successfully entered (131 ±19 mm) the 50cm slippery-panel pot than for those that failed (111 ±20 mm) (Welch's t-test, df = 56.121, p = 0.00025; Fig. 16).

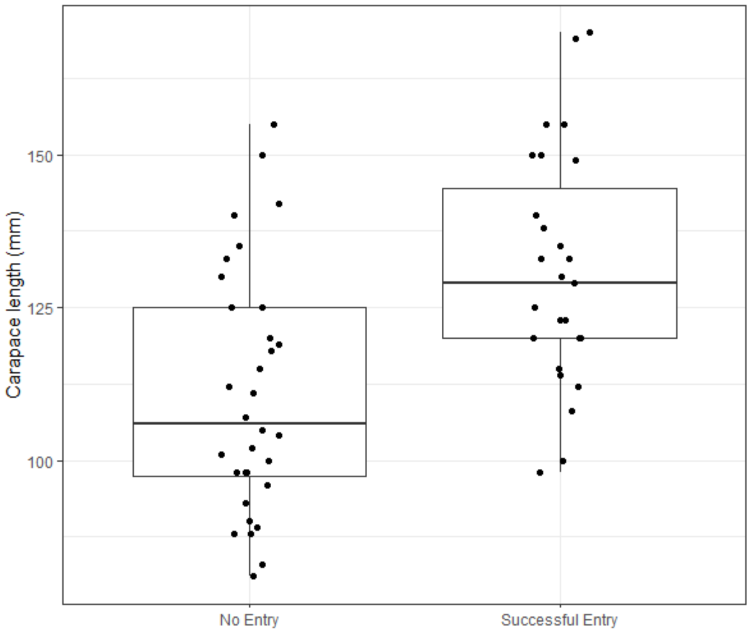

Figure 16: Carapace length and successful attempts. Carapace length (mm) for all crabs attempting to enter the 50cm slippery-panel pot, separated into two groups. Those who failed to enter the pot, and those who succeeded

CL was found to have a significant effect ($p = 0.00139$) on entry (Fig 17.a), where the larger crabs had a higher probability of entry (model 1). The CL of crabs with 50% probability of entry (L50) was 124mm, and difference in CL between crabs with 75% and 25% probability of entry (SR = L75-L25) was 43 mm. Removing CL from the model substantially harmed the fit (Wald test, $p = 0.00226$). However, the pseudo R^2 (McFadden´s $R^2 = 0.16614$) produced suggest a large proportion of unexplained variation. For the second model (model 2), CL was found to have a significant effect ($p = 0.000159$) on REACH (reaching inner funnel edge) (Fig 17.b), where the larger crabs had higher probability of REACH. L50 was 117mm and SR was 28mm. Removing CL from the model substantially harmed the fit (Wald test, $p = 0.00038$). By using McFadden´s R^2 (0.29761), the predicting power of this model was found to be slightly stronger than that of the model 1.

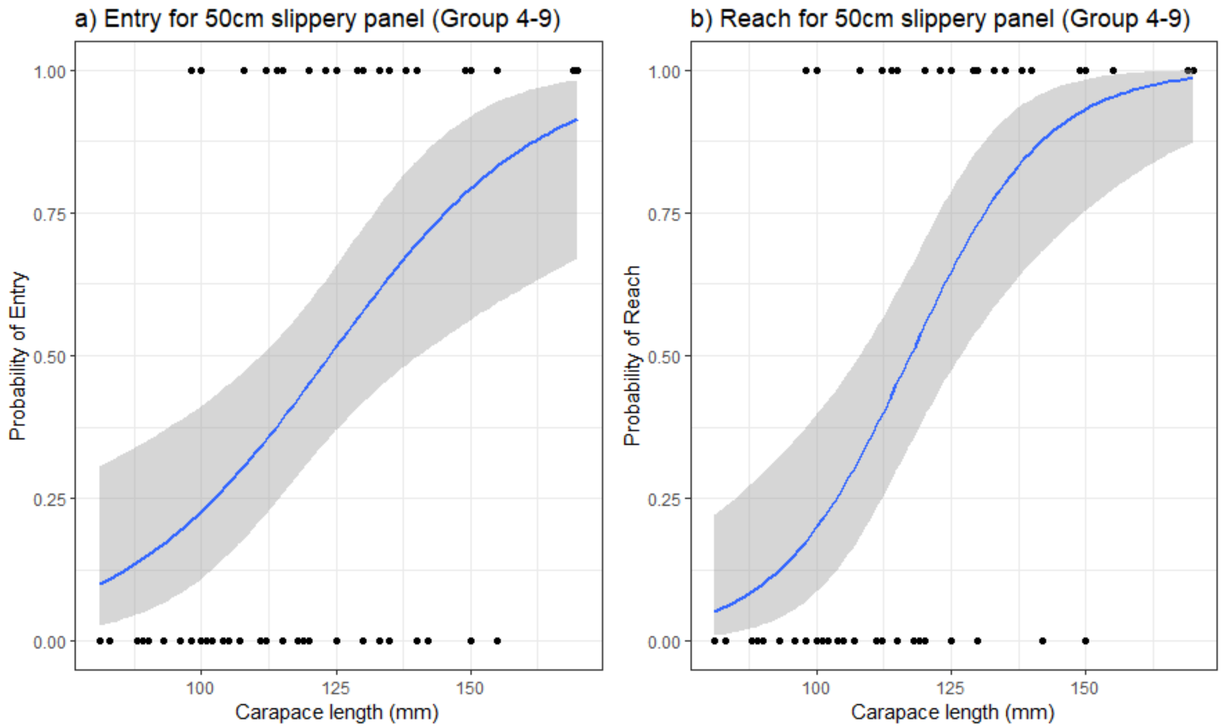

Figure 17: a) Model predicted probability of successful entry as a function of carapace length (mm), with a grey 95% confidence interval band. Dots represent crabs observed in experiment, where 1 = successful entry and 0 = no entry. L50 = 124 mm, SR (L75-L25) = 43mm. b) Model predicted probability of REACH (Crab successfully reaches the inner edge of slippery panel, with foot or claw) as a function of carapace length (mm), with a grey 95% confidence interval band. Dots represent crabs observed in experiment, where 1 = REACH, and 0 = NO REACH. L50 = 117 mm, SR (L75-L25) = 28 mm.

Out of 31 crabs which managed to reach the inner edge of the funnel, only four crabs failed to enter the pot. The rest of the crabs successfully entered, regardless of their CL (Fig. 18). The four crabs that failed to enter did all have CL over 130mm. Three of these crabs made one attempt and the last crab made 8 attempts to enter.

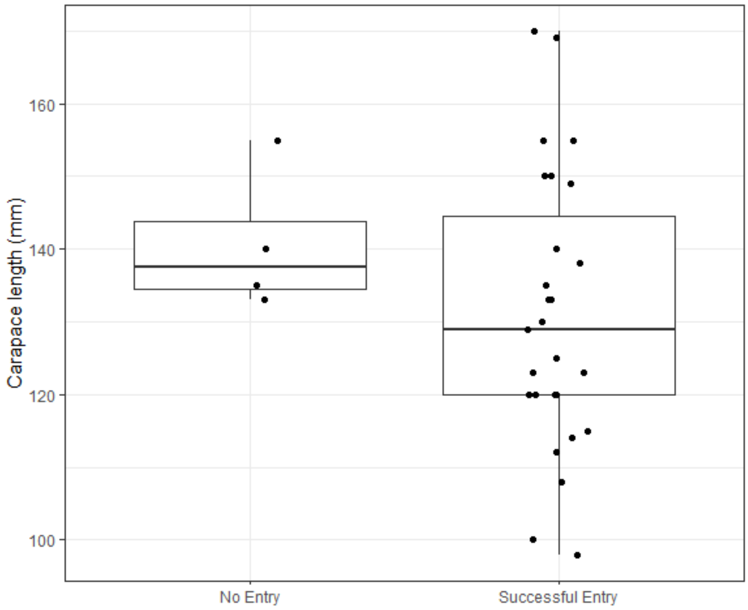

Figure 18: Carapace length and outcome (No entry, Successful entry) for all crabs that REACH (Crab successfully reaches the inner edge of slippery panel, with foot or claw). Each dot represents a crab from group 4-9 that managed to REACH for the 50cm slippery-panel pot. Observations: No entry (n = 4), Successful entry (n = 27)

3.1.3 Entry effort

There was an observable difference in number of entry attempts between the control and 50cm slippery-panel pot (Fig. 19). 76% of the crabs made exactly one attempt on the control pot, while only 27% made one attempt on the experimental pot. The majority of crabs made two or more attempts on the experimental pot, with the two most extreme individuals making 24 and 14 attempts.

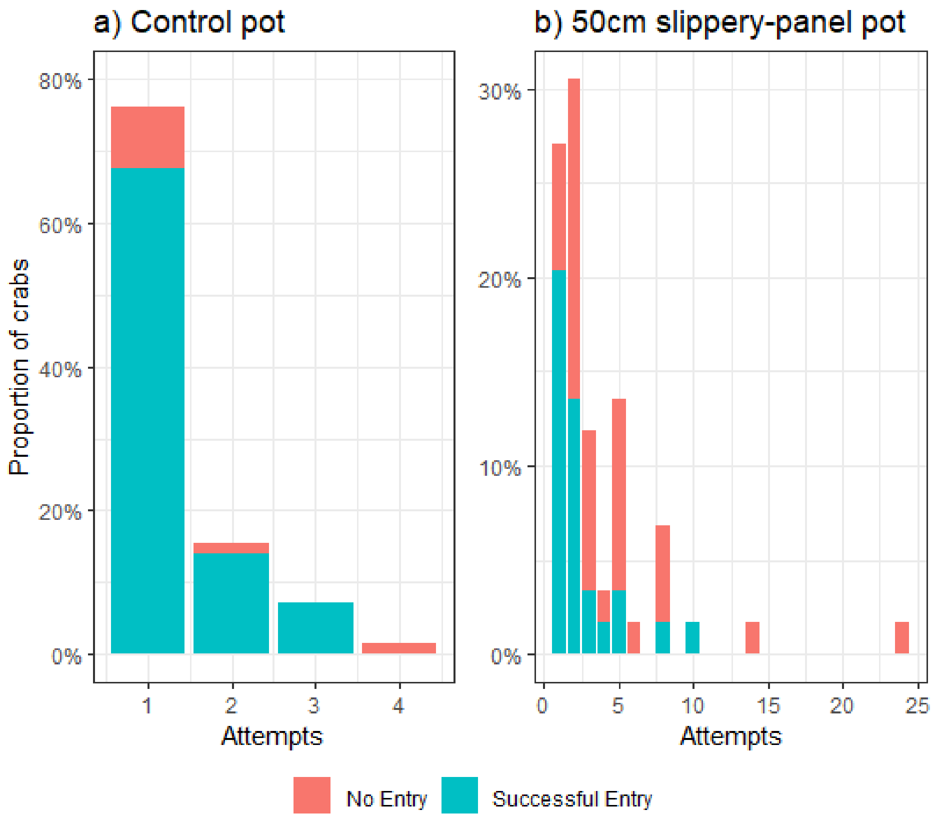

Figure 19: Entry effort. The y-axis represents the proportion of crabs with exactly x attempts, where 100% includes all crabs which attempted to enter the corresponding pot. Red represents the crabs that never entered the pot, while blue represent the crabs that successfully entered the pot. Observations per pot; a) n = 71, b) n= 59.

The entry rate for each attempt was considerably greater for the control pot (58.8-83.3%) than for the 50cm slippery-panel pot (5.6-22%) (Fig. 20). Whereas the entry rate was relatively similar for the first three attempts on the control pot, the entry rate dropped drastically from the first two attempts to the third and fourth attempts on the 50cm slippery-panel pot. The entry rate increased again for attempt 5 (12.5%) and 8 (14.3%), but with decreasing observations. Apart from one crab that entered on its 8th attempt, the majority entered on the 1st and 2nd attempt, while some had up to five attempts.

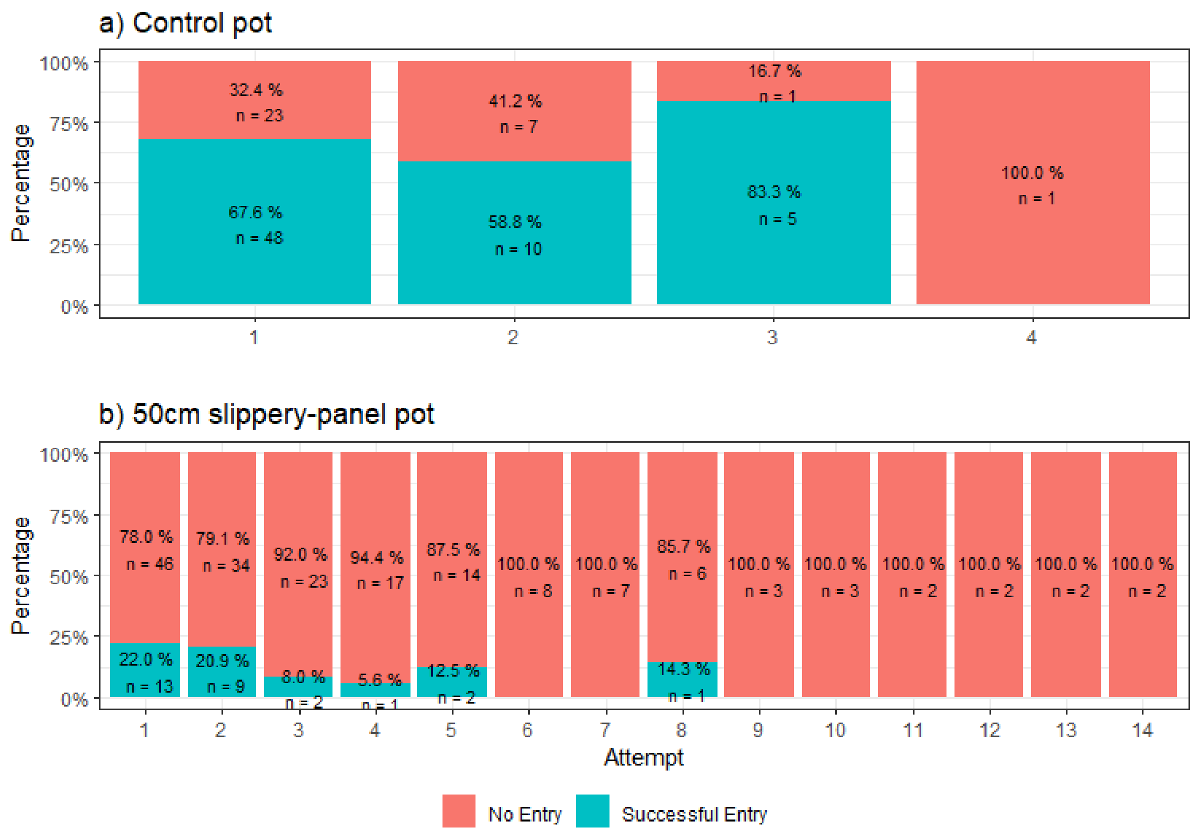

Figure 20: Entry rate per attempt. Proportion of successful (blue) and failed attempts (red) for the 1st attempt, 2nd attempt, etc. There was an individual which had 24 failed attempts on entering the 50cm slippery-panel pot. Attempt 15 and upwards are not displayed on figure b) for practical reasons. Attempt 15 – 24 are all: 100% no Entry, n = 1.

3.2 Behaviour comparison between the control pot and 50cm slippery-panel pot

3.2.1 Duration of entry attempts

Mean duration for successful attempts was found to be significantly greater for the 50cm slippery-panel pot C (105.56 ±72.19 s) than for the control pot (47.78 ±34.87 s) (paired t-test, df = 17, p-value = 0.0074) (Fig. 21b). A paired Wilcoxon signed rank test was used to confirm the difference between the 50cm slippery-panel pot and the control pot (p = 0.012). When including all successful observations, the mean attempt durations were 103.48 ±67.17 s for the 50cm- slippery-panel pot and 36.65 ± 17.15 s for the control pot (Fig. 21a).

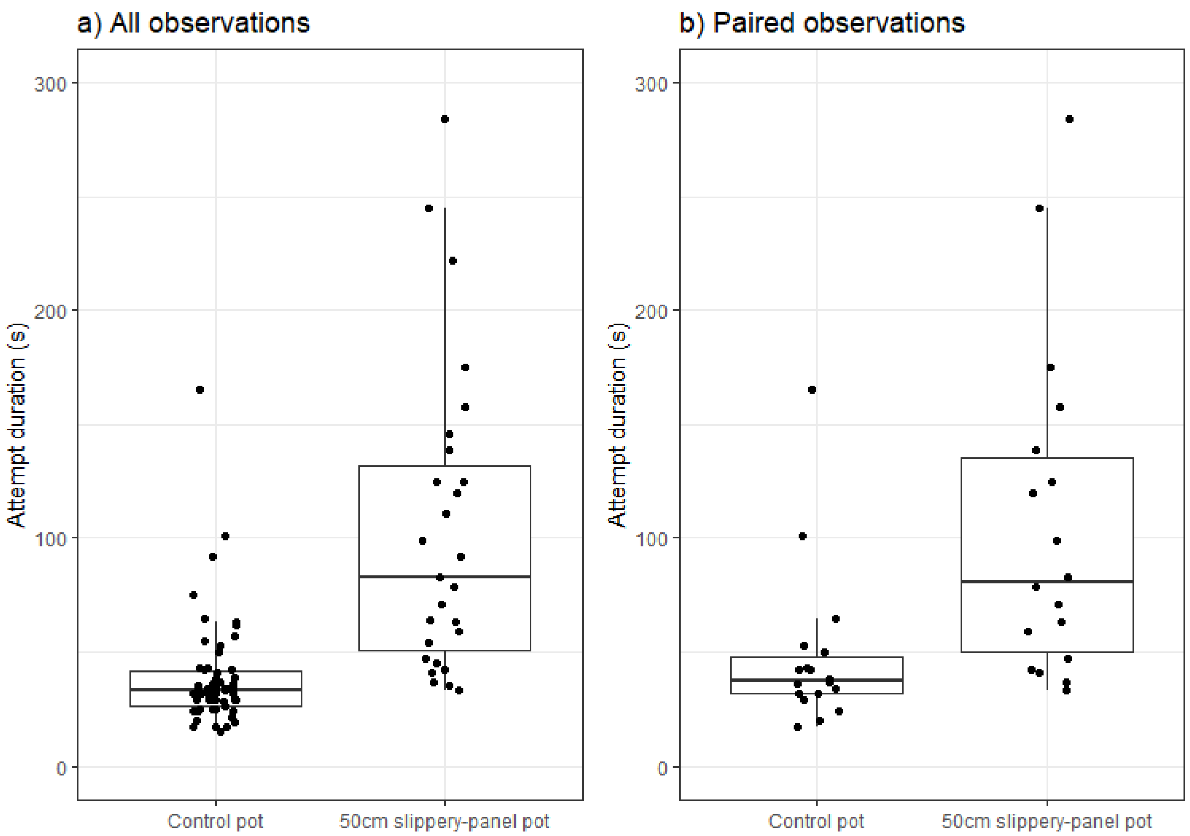

Figure 21: Time spent in funnel during successful entry attempts on the control pot and 50cm slippery-panel pot. A) All successful attempts, b) Only crabs with successful attempt on both pots. Observations: a) Control pot (n =58), 50cm slippery-panel pot (n = 27), b) Control pot (n = 18), 50cm slippery-panel pot (n = 18)

3.2.2 Number of attempts

The smaller individuals (CL ≤ 120mm) showed a clear increase in the number of entry attempts on the experimental pot, compared to the control pot (Fig. 22). In the control, 88% of the crabs had exactly 1 attempt, whereas only 21% of the crabs had exactly 1 attempt for the experimental pot. While no crabs had more than two attempts on the control, 52% of the crabs had more than two attempts on the experimental pot. Most of the larger crabs (CL > 120mm) had a single attempt on the control pot (66%), while only 34% had a single attempt on the experimental pot. It was more common to have two or more attempts on the experimental pot than on the control pot.

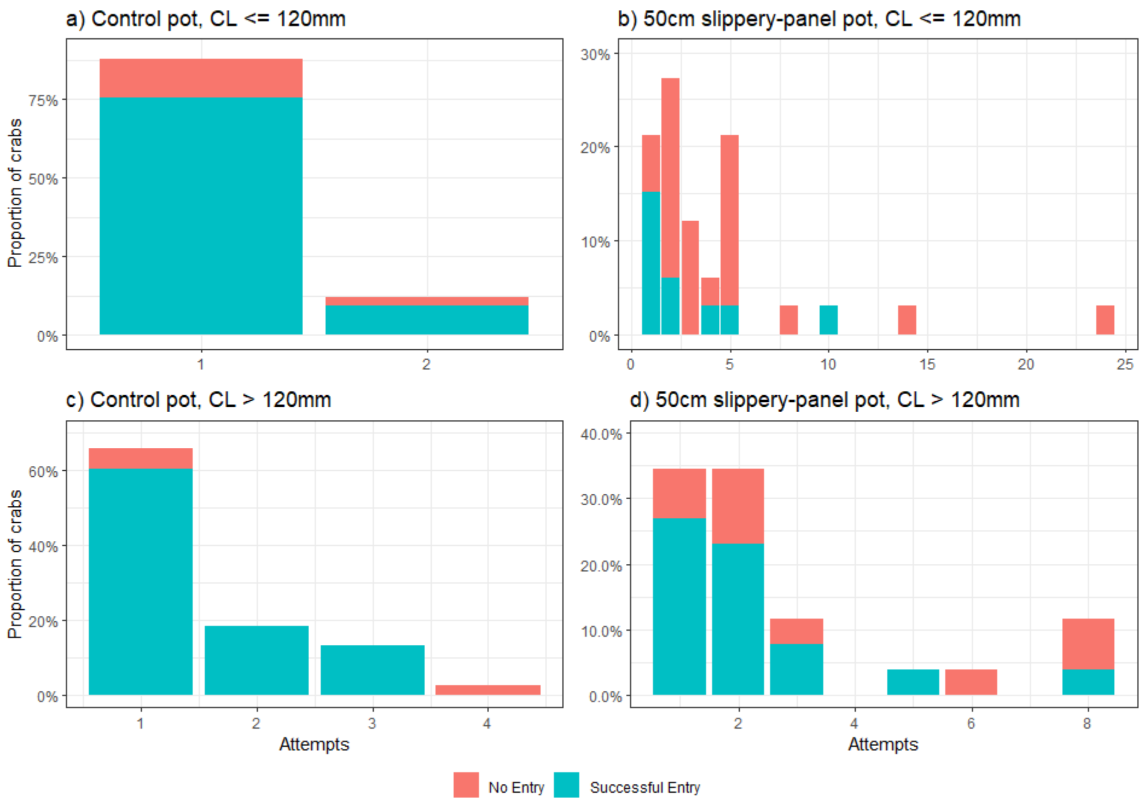

Figure 22: Attempts made per individual for control pot and 50cm slippery-panel pot. Blue represents the crabs that successfully entered the pot, red represent the crabs which never succeeded. A) Showing crabs with 120mm carapace length (CL) or smaller for the control pot. B) Showing all crabs with 120mm CL or smaller for the 50cm slippery-panel pot. C) Showing all crabs with CL greater than 120mm for the control pot. D) Showing all crabs with CL greater than 120mm for the 50cm slippery-panel pot

3.2.3 Carapace orientation

There was a clear difference in distrubution of carapace orientation between the control pot and the 50cm slippery-panel pot (Fig. 23). The majority of small and large crabs entered the experimental pot sideways, with 80% and 76% respectively. Comparatively, only 46% of small crabs and 26.7% of large crabs entered sideways for the control pot. Entering the pot with carapace facing forward was more common for the control pot (32-50%) than the experimental pot (10-12%), for both size groups. Carapace orientation transitions indicate how many times a crab changed the carapace orientation (CFWD, COLBQ, CBCK, CSIDE; Table 2) in relation to the inner funnel edge when attempting to enter the pot. There was no clear difference in number of carapace transitions between the control and experimental pot for small and large crabs (Appendix 7).

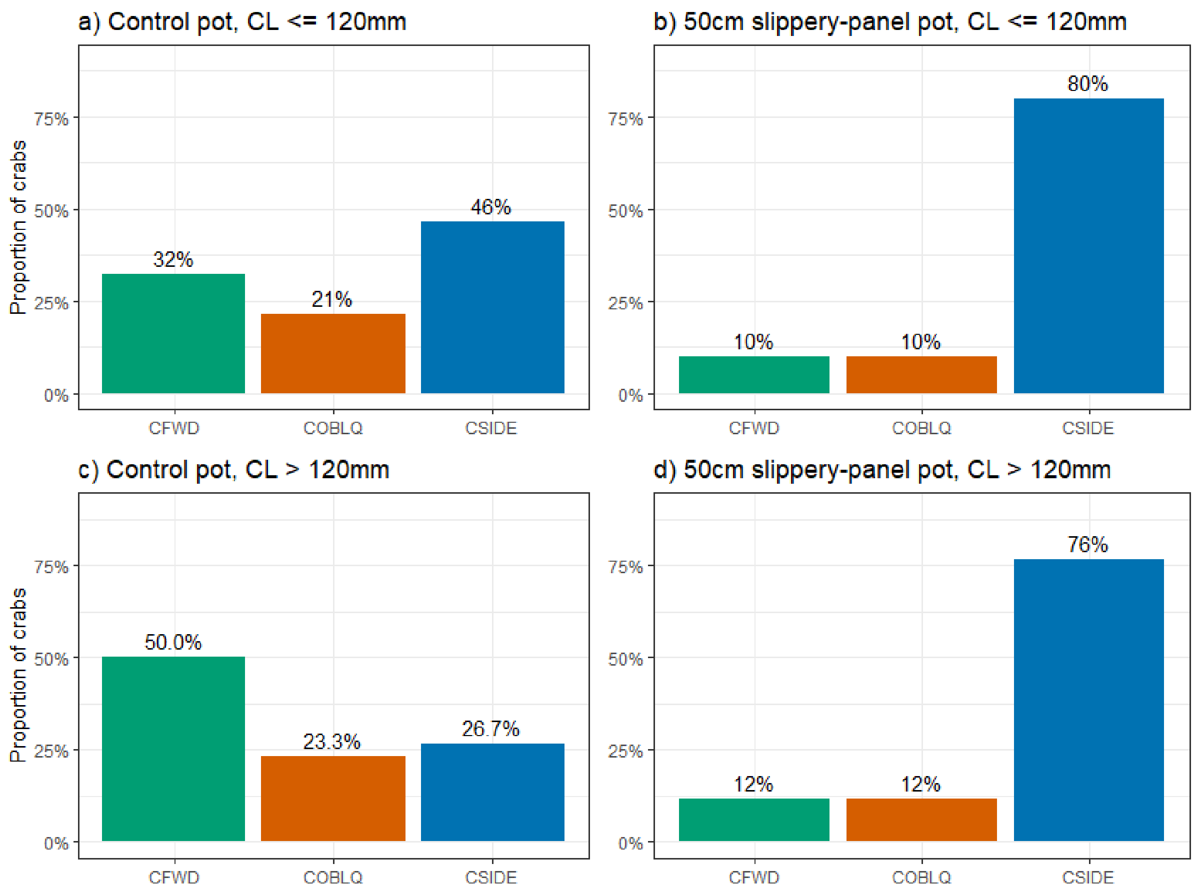

Figure 23: Carapace orientation for all successful entries on the control pot and 50cm slippery-panel pot. Observations per pot; a) n = 28, b) n = 10, c) n = 36, d) n = 17. CFWD = Carapace forwards, COBLQ = Carapace obliquely, CSIDE = Carapace sideways, all in relation to the inner funnel edge (Fig. 14).

3.2.4 Crab positioning in funnel

Most of the crabs entered the pots via panel A+B for both the control pot and 50cm slippery-panel pot (Fig. 24). The smaller crabs (CL ≤ 120mm) displayed a relatively similar distribution between the panels in contact with for the control and experimental pots. With a slightly lower proportion of smaller crabs entering the control pot (7%) in contact with panel B+C than for the experimental pot (20%). One larger crab (CL > 120mm) entered the control pot only being in contact with panel A. A greater proportion of the larger crabs (CL >120mm) entered the experimental pot (65%) in contact with panel A+B than for the control (46.7%). The biggest difference between the control pot and the experimental pot was the proportion of crabs entering while in contact with panel B+C, with 26.7% and 6% respectively.

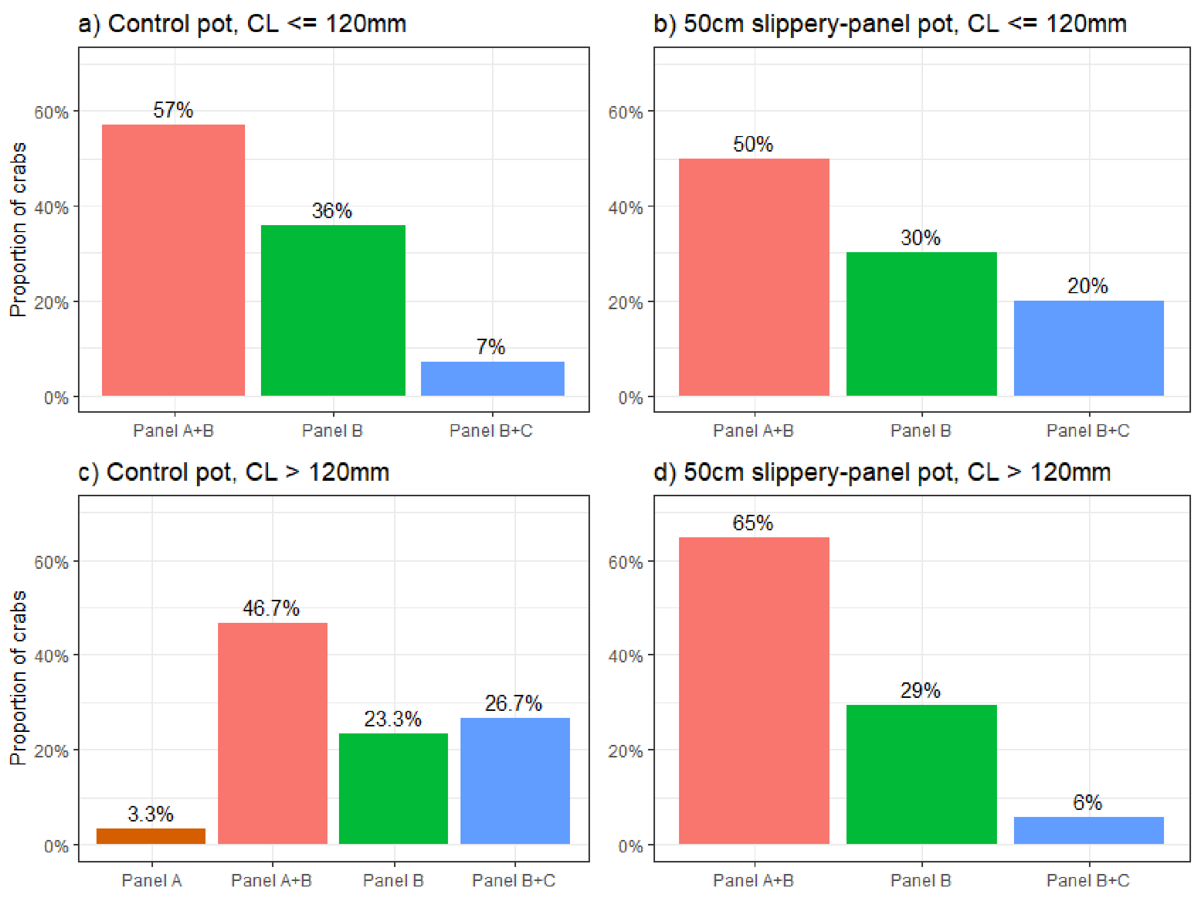

Figure 24: Successful entries via panel (A / A+B / B / B+C; Fig. 13) on control and experimental pots. Separated into two group, crabs with carapace length ≥ 120mm or < 120mm. Observations per pot; a) n = 28, b) n = 10, c) n = 36, d) n = 17

3.3 Behaviour for successful and failed entry attempts on the 50cm slippery-panel pot

3.3.1 Inner mesh wall (IMW)

Use of the inner mesh wall (IMW) between the funnels (Fig. 14) was observed to give an advantage in surpassing the selection barrier, where 81% of the crabs successfully entered the pot used the IMW. The use of IMW on successful entry was prominent for all crab sizes (Fig.25). There was a clear difference in the presence of IMW in the successful attempts (22/27) and the first failed attempt (1/46). First failed attempt was used for comparison to avoid having repeated observations per individual. If including all failed attempts, there were only two observations of IMW in total.

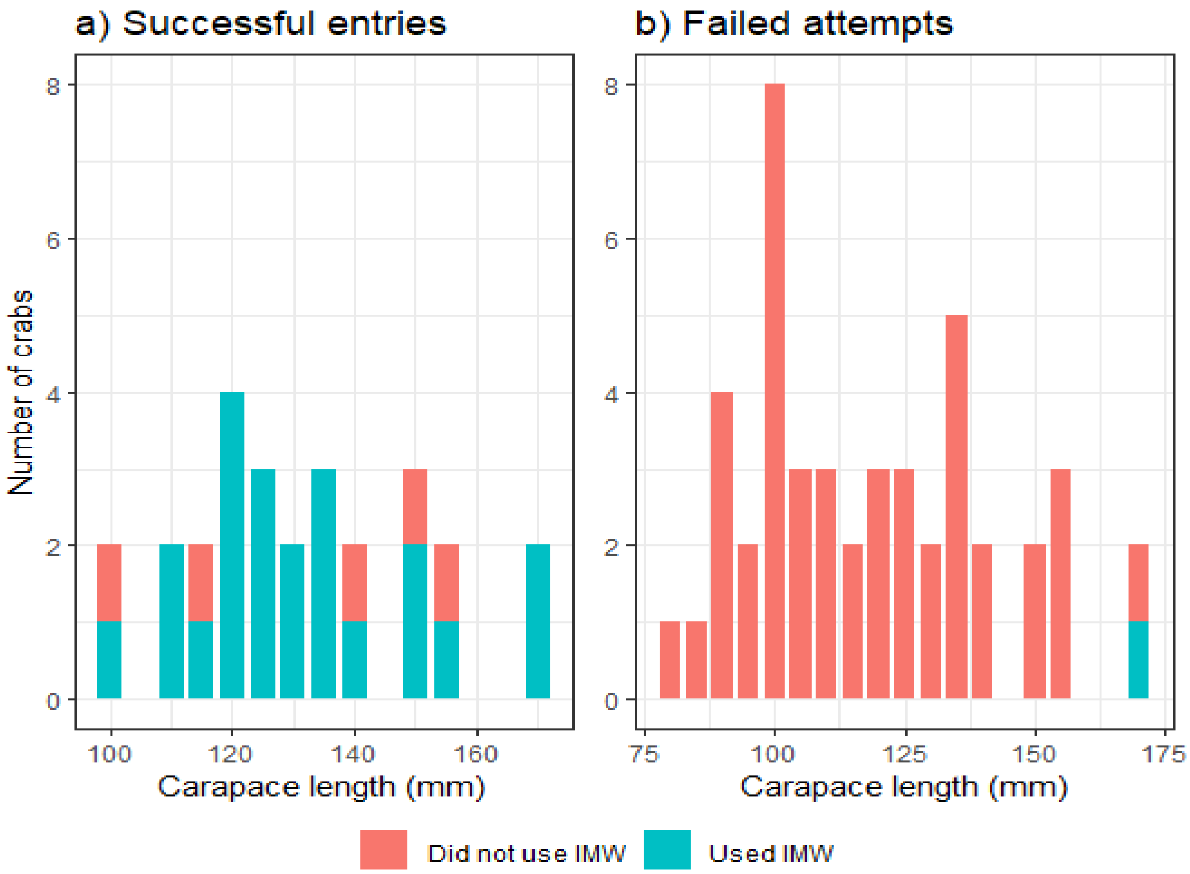

Figure 25: Use of inner mesh wall (IMW) for successful entries and failed entry attempts. Figures display Carapace length in 5 mm brackets. A) Display all successful entries on the 50cm slippery-panel pot. B) Displays the first failed attempt on entry, for each individual crab attempting. Only first attempt is included to avoid repeated measurements per individual. Red represents attempts not including IMW, blue represent attempts including IMW. Observations per plot: a) n = 27, b) n = 46.

3.3.2 Cut in slippery panel (CUT)

From the observations, it seemed like the usage of the CUT (cut in slippery panel; Fig. 15) occasionally aided the crabs in reaching the inner funnel edge, especially for the smaller ones that did not reach across to the edge so easily. The use of CUT was more commonly observed for the crabs which successfully entered (9/27) the pot, than those that failed (2/46) (Fig. 18). The CUT was more frequently used by the undersized crabs (CL < 130mm) that successfully entered the pot, than for the legal sized crabs (CL ≥ 130mm), 54% (n = 7) and 14% (n = 2) respectively (Fig. 26).

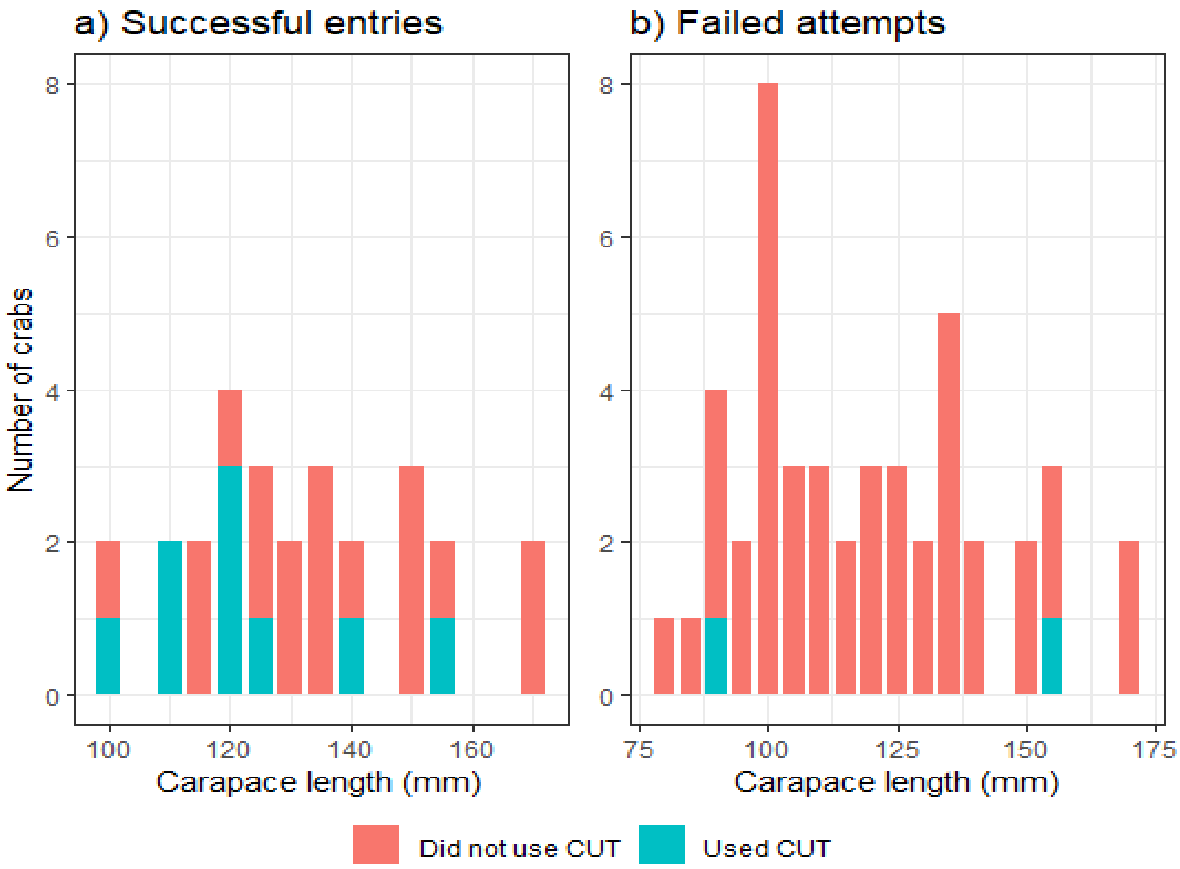

Figure 26: Use of cut for successful entries and failed entry attempts. Figures display Carapace length in 5 mm brackets. A) Display all successful entries for the 50cm slippery-panel pot. B) Displays the first failed attempt on entry, for each individual crab attempting, for the 50cm slippery-panel pot. Only first attempt is included to avoid repeated measurements per individual. Red represent attempt not including CUT, blue represent attempt including CUT. CUT is a slit in panel A as a result of patchwork. Observations per plot: a) n = 27, b) n = 46.

3.3.3 Individual variation in carapace orientation and crab positioning for failed and successful entry attempts.

Comparison of carapace orientation and crab position in the funnel was conducted on individual level. Using data from crabs that had one or more unsuccessful attempt before successfully entering the experimental pot (n = 14). The comparison was done between the successful entry attempt and the first failed entry attempt for the 50cm slippery-panel pot.

A significant relationship between carapace orientation and successful/failed entry attempts was found (Fisher's Exact, p = 0.0056), where the majority of crabs walked sideways (86%) on successful entry attempts and forward on (42.9%) failed entry attempts (Fig.27). The most common carapace orientation (CFWD) for the failed attempts was not observed for the successful entries.

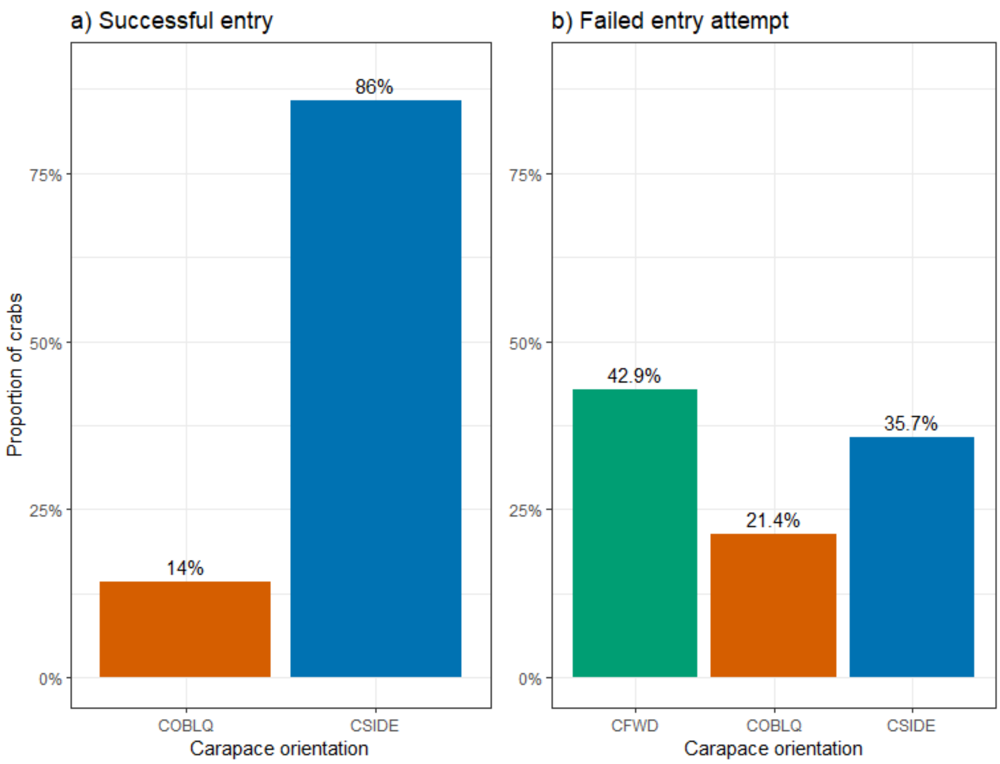

Figure 27: Carapace orientation for successful (a) and failed (b) entry attempts for the 50cm slippery-panel pot. Individuals which failed their first attempt, but later succeeded in entering were used to produce these figures. Thus, the same individuals represent both outcomes. Carapace orientation was recorded in relation to the inner funnel edge (Fig. 14), at the end of the attempt. CFWD = carapace forward, COBLQ = Carapace obliquely, CSIDE = Carapace sideways. Observations: n = 14

Crabs were more commonly in contact with panels A+B (57%) on successful attempts and panel B on the failed attempts (57%) (Fig. 28). No significant relationship between crab position in funnel and successful/failed entry attempt was found (Fisher's Exact, $p = 0.4071$).

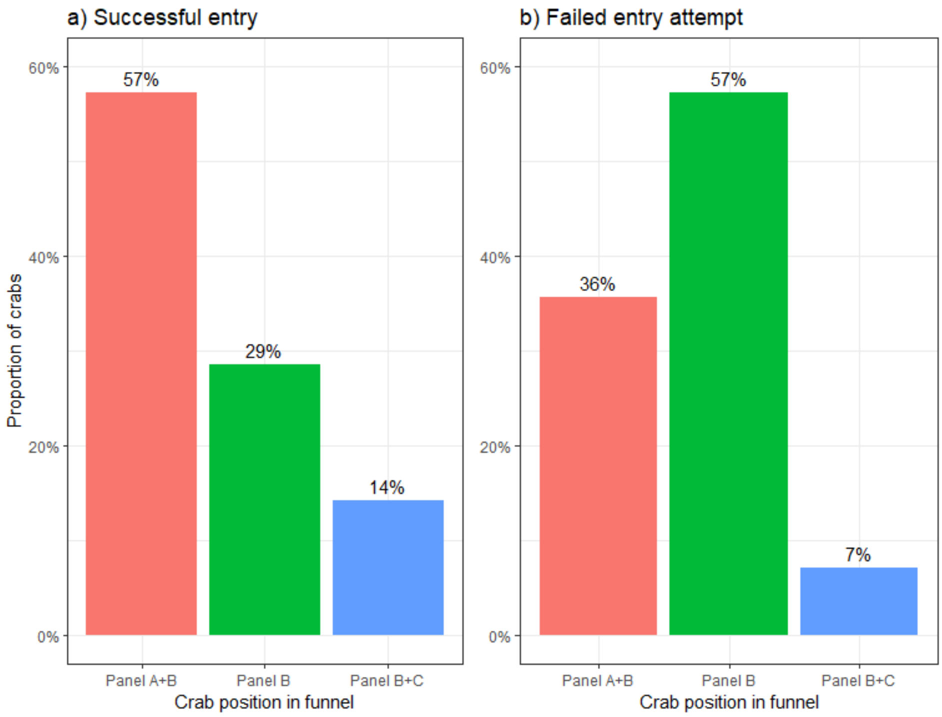

Figure 28: Crab position in the funnel for successful (a) and failed (b) entry attempts (Table 2, Fig. 13). Individuals which failed their first attempt, but later succeeded in entering were used to produce the figures. Thus, the same individuals represent both outcomes. Crab position in funnel was recorded at the end of the attempt. Observations for figures: n = 14

3.4 Two-Chamber pot

None of the five legal sized crabs (CL ≥ 130mm) in group 2-6 descended into the escape chamber during the experiment (Fig. 9), while 85% of the 68 undersized crabs (CL < 130mm) did descend (Fig. 21). No crabs were observed to ascend back up to the upper chamber.

CL was found to have a significant effect on escape probability (p = 0.002577) (model 3), with smaller crabs having a higher probability of descending to the escape chamber (Fig. 29). L50 and SR was estimated to be 128 mm and -25 mm respectively. Removing CL from the model significantly reduced the model fit. (Wald test, p= 0. 00357). A pseudo R^2 was produced to estimate the prediction power of the model (McFadden´s R^2 = 0.25263).

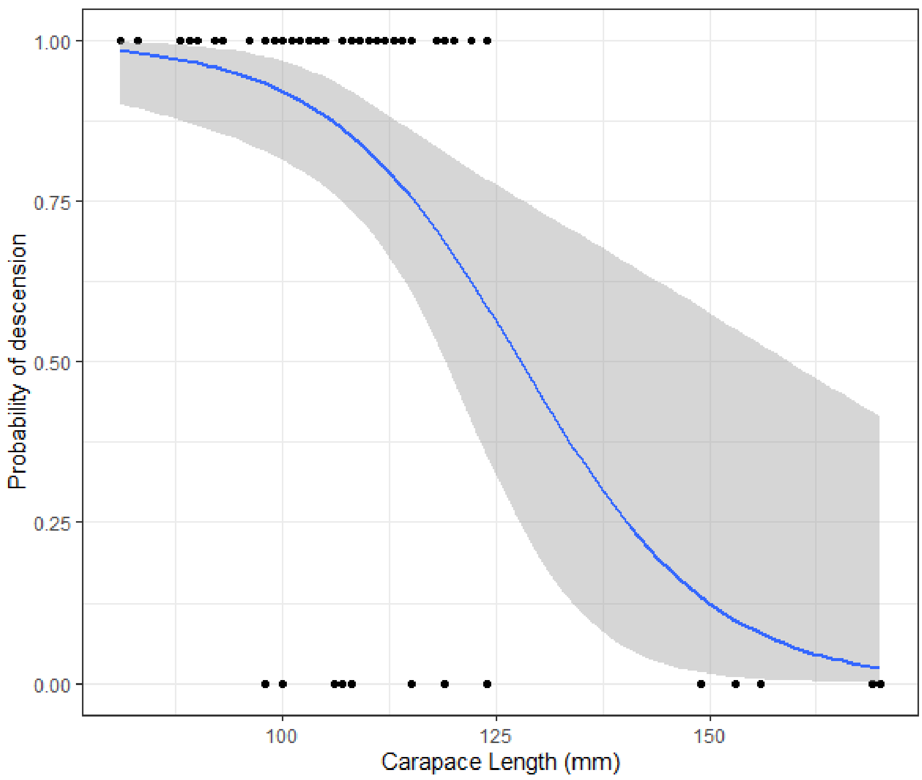

Figure 29: Model predicted probability of descension to escape chamber as a function of carapace length in mm, with 95% confidence intervals (grey band). Dots represent individual crabs observed in the experiment (groups 2-6), where 1 = descent and 0 = no descent. L50 = 128 mm, SR (L75-L25) = -25mm. Observations: total n = 73, descent (1) n = 58, no descent (0) n = 15.

4. Discussion

The square pots used in the Red King crab fishery is considered a passive type of fishing gear, where its catch efficiency relies heavily on the behaviour of the target species. Therefore, when implementing a mechanism for size selectivity, both for the capture and escape process, the modifications will also rely on the behaviour of target species. Thus, this study quantitatively described capture efficiency for a pot modified with a selection barrier, crab behaviour during capture process, and efficiency of an escape chamber.

4.1 Limitations and potential sources of error

Light is necessary in order to quantify the behaviour of Red King crab when attempting to enter a baited pot. As the experimental trials lasted longer than daylight, artificial light had to be used. The artificial light was constant during the entire entry experiment, and therefore the crabs were not able to distinguish between night and day.

For the escape experiment, no artificial light was used for group 1 and 2. However, while reviewing the video recordings, there were not sufficient light to make observations for several hours of the night. Thus, artificial light was added for groups 3-6. Ideally, all groups should have the same light conditions

No clear diel activity rhythm was observed for RKC during a walking speed and area utilization experiment performed during July/August (Jørgensen et al. 2007). As the experiment was performed in the north of Norway during the summer, the authors suggested that the midnight sun or chemically stimulated searches could be the reasons for no difference between night and day. Based on this and keeping the light constant for all trials (except for escape trial for groups 1-2) and pot types, I expect no fluctuations in activity levels between the trials.

4.1.1 Entry experiment

In the initial study design with 6 groups of crabs, three groups were to be exposed to the slippery-panel pot before the control pot, and three groups to the control pot first. This would allow to see if the order of exposure to the different pots would influence the number of crabs attempting to enter the pots. The results from the pilot study indicated that a slippery panel of 25cm should be sufficient. However, as the main study proved otherwise, the first three trials (groups 1-3) were used to find a more suitable panel width. Since the pot was modified after the three first groups, an extension of the experiment had to be performed, with three new groups (groups 7-9). The three new groups were exposed to the slippery-panel pot first, to maintain the system for exposure order. The crabs of the three new groups (group 7-9) had larger average CL (136.5 ± 11.2 mm) than the crabs in group 4-6 (107.8 ± 18.6 mm). Thus, the smaller crabs of the experiment were exposed to the control first, while the larger crabs were exposed to the slippery-panel pot first. Ideally, the groups should have had a similar mean CL and be exposed to the two pots in different order, to able distinguishing between the effect of order and CL.

Due to the unforeseen increase in slippery panel size, from 25cm to 30cm and then to 50cm. I did not have sufficient material to make full sized 50cm panels. Therefore, I had to patch together the two smaller panels to produce the 50cm panels. For that reason, one of the 50cm panels had a slit, referred to as a CUT. Some crabs utilized this CUT in their attempt to enter the pot. Thus, usage of the CUT was recorded and included in the behavioural analysis. Ideally, the slippery panels should be made of whole pieces of fabric, and not patched together.

This study was not designed to investigate the effect of odour plume on search behaviour, which is likely the reason for the following opposing observations. Typically, RKC following an odour trail is expected to approach a pot from a downstream position (Zhou and Shirley 1997b; Stiansen et al. 2010). However, most crabs in the current study attempted to enter from an upstream position. In order to investigate the effect of odour plume on search behaviour, future study design would require some modifications. Firstly, the odour spread in the tank must be determined prior to the experimental trials. Secondly, the crabs would require several hours of acclimatising, to not be hyperactive when the pot is introduced. Further, the pot and bait must be introduced to the tank after the crabs to allow the odour plume from the bait to be fresh and not spread around in the tank prior to introducing the crabs. Limiting the observation window to match the odour plume spreading in the tank is probably wise. Lastly, high water inflow/outflow or replacing the water content in the tank should remove bait residue and odour, which otherwise could be confusing for the next group of crabs.

In addition to chemotaxis leading to entrapment of RKC, the crabs can also be motivated by visual cues or sounds emitted by other crabs feeding on bait (Miller 1979; Tolstoganova 2002). Furthermore, as *Carcinus maenas* have succeeded at learned complex mazes motivated by food in laboratory conditions, and showed clear indication of remembering the maze two weeks later (Davies et al. 2019). All crabs used in this experiment have previously been caught with pots of the same type as the control pot. It is therefore possible they associate pots with access to food and enter due to association.

4.1.2 Behaviour analysis

Two of the behaviour categories from the ethogram were recorded but not included in the results. One of these categories were GRIP, which was an event indicating that the crab used its claw to grip the inner edge of the funnel. Initially some crabs were observed doing this, and it was hypothesised this could be beneficial to their entry success. However, as the camera was aimed at the funnel in a fixed position, it was not always possible to observe if the crabs grabbed on to the inner funnel edge or not, particularly if the crab had its back directly facing the camera. Thus, it was not possible to record if GRIP occurred or not for a large proportion of the entry attempts, and it had to be removed from the analysis.

The other behaviour category not included in the results were MORE, which indicated that an additional crab attempted to enter the pot at the same time as the focal subject. The behaviour categories were based on preliminary observations, in which the definition of the behaviour category MORE seemed reasonable. However, upon reviewing all entry attempts from the video footage, it became apparent that the category required subcategories or modifiers. As used in behavioural sampling, the category only indicated if an additional crab was present or not. When two crabs were present in the funnel at the same time, the focal subject were seen to be unaffected, impaired or benefit from the presence of the other crab. Thus, it should also include if the two crabs came in contact with each other, and if the contact was beneficial or not for the success of entry attempt. This was particularly the case for the slippery-panel pot due to the crab's difficulty in surpassing the slippery panel. When two or more crabs were in the funnel at the same time, but not in contact, typically no effect was observed. However, when the crabs came in contact with each other, the most common outcomes were that they either used each other as foothold, or the smaller crab pulled away. In the first scenario, the effect of MORE could be beneficial to one of the crabs and disadvantageous to the other crab. In the latter scenario, the smaller crab was usually restricted, while the larger crab was unaffected. Although less common, it was also observed that two large crabs (of similar size) exhibited aggressive behaviour towards each other in the funnel, resulting in a disadvantage for both crabs. For future behavioural sampling, I would place the camera in a position so that I can record the occurrence of each of the scenarios described above, to better quantify and determine the effect of MORE and GRIP on entry success.

4.1.3.1 The behavioural categories effect on entry success

The ethogram was developed with the purpose of modelling the probability of successful entry, with the behavioural categories and CL as predicting variables. The experiment setup and ethogram were aimed at using a Generalized linear mixed effect model (GLMM) to determine the effect of the different behavioural categories, with crab ID as random effect. Including crab ID as random effect in the model was necessary due to the repeated measurements (multiple entry attempts) for most of the crabs. When attempting to model the probability of successful entry given the behavioural categories, it resulted in a singular fit, even for the simplest models with only one predictor variable. The singular fit means the random effect structure was too complex to be supported by the data, however, the random effect could not be changed or removed. Without crab ID as random effect, the model would be using psedoreplicates due to the repeated measurements. Thus, I had to use alternative means to investigate the effect of the behavioural categories on the successful entry rate. To avoid singularity in future similar study, I would perform the behaviour sampling in a manner which avoids repeated measurements. However, repeated measurement might be necessary depending on research question.

4.2 Discussion of results

4.2.1 Catch efficiency

This study demonstrated a decrease in entry rate for undersized (CL > 130mm) crabs with increasing size of slippery panel (Table 3). While the widest panel (50cm panel) showed a significant decrease in entry rate for undersized crabs (Chi square test, $p < 0.001$), there was no significant decrease in entry rate for the legal sized crabs (Fisher's Exact, $p = 0.067$). Furthermore, CL was 124 mm for the estimated 50% probability of entry (L50 = 124 mm), which is close to the minimum catch size (CL = 130 mm). Though, it's important to mention that the selection curve was not particularly steep (Fig. 17.a; SR = 43 mm). The results of this study corresponds with the findings of Chiasson et al. (1993), where they saw a decline in number of undersized snow crab caught with an increasing panel height, when testing slippery panel around the top entrance of conical snow crab pots.

The significant reduction in entry rate for undersized crabs (From 0.88 to 0.36) due to adding a 50cm panel, and the average CL of the individuals that successfully entered the pot (131 ±19 mm) being greater than for those that failed (111 ±20 mm) (Fig. 16), suggests that the slippery panel works as intended in hindering most undersized crabs from entering. However, there is still room for improvement as some (36%) of the smaller individuals manged to enter, where the two smallest individuals had a CL of ca 100mm. Additionally, the pseudo R^2 computed for both model 1 (R^2 = 0.16614) and model 2 (R^2 = 0.29761) were low, indicating that a large proportion of variance is not explained by CL. This is likely due other influential factors like the behaviours IMW, CUT and Carapace orientation, which seem to increase probability of successful entry. Although removed from the analysis due to the reasons discussed above, it is also possible that GRIP affect the probability of successful entry.

The reasoning for a 50cm selection barrier was based of observations from the pot with 25cm and 30cm panel, where the crabs frequently pushed themselves over the edge. By increasing the panel to a width of 50cm, it was expected that the smaller crabs would not be able to push themselves over the edge. However, in the main experiment it became apparent that crabs that managed to REACH (31 out of 35) usually succeeded in entering the pot (Fig. 18). This suggests the size selectivity provided by the 50cm panel has an effect in that it prevents crabs from REACH. Not by preventing crabs from pushing themselves over the edge, as first expected. A comparison of the model predicted selection curve for entry (model 1; L75 – L 25 = 43 mm) and REACH (model 2; L75 – L25 = 28 mm) supports this, as the model for REACH has a steeper curve and explains a larger proportion of the variance (Fig. 17).

Interestingly, all four crabs that failed to enter the pot after reaching the inner funnel edge (REACH) had a CL over 130mm (Fig. 18). This could be an indication that it is more challenging for larger crabs to get over the edge when reaching it. However, with only four observations, no conclusion can be drawn. It is also possible the four crabs were not sufficiently motivated to force the selection barrier, as three of the four only had one attempt at entering the pot.

In general, the crabs had more attempts and a lower entry rate per attempt on the experimental 50cm pot than the control pot, indicating an increase in effort to enter the experimental pot (Fig. 19; Fig. 20). All crabs were starved for a week, so they should be equally motivated to enter both pots to feed. Additionally, the crabs were confined to a limited area along with the pot. Continuing the search elsewhere or move to a different location was therefore not an option. Thus, it is possible the increased effort required by some crabs may have a greater effect on entry rate in the wild, where the effort and time committed depends on motivation, surrounding elements and potential reward (Sih and Christensen 2001; Chakravarti and Cotton 2014).

4.2.2 Behaviour comparison between the control pot and the 50cm slippery-panel pot

The crabs entered the control pot relatively quick (Fig. 21), similar to what previous studies have observed (Zhou and Shirley 1997b; Stiansen et al. 2010). There was a slight difference in duration between the previous studies and this study. Zhou and Shirley (1997b) reported that the crabs used between 0.22 and 3.02 min (average < 1 min) to enter the pot, Stevens et al. (2010) recorded that 55% of the crabs captured entered within 90 sec of initiating vertical search, while I recorded an average entry duration of 47.78 ±34.87s for the paired individual observations and 36.65 ± 17.15 for all observations. The difference can presumably be explained by difference in definitions or pot design. Zhou and Shirley (1997b) defined the duration as from when the crab inserted a leg into the funnel, Stiansen et al. (2010) defined the duration from when a vertical search was initiated, and I defined the duration from when the entire carapace has passed the bottom metal frame and is fully in the funnel.

Paired individual observations indicated that the crabs used significantly more time to enter the 50cm pot than the control pot (Fig. 21; paired t-test, df = 17, p-value = 0.0074), demonstrating that the addition of a 50cm slippery panel affected the time invested by RKC to enter the pot. Although, statistical tests were only applicable to the paired observations of same individuals, a general difference in duration is also seen for all observations (Fig. 21). Suggesting the trend found for the paired observations likely is true for all observations. The increase in average duration used for entering the 50cm pot was expected mainly due to the surface texture of the panel. The panel used were a slippery tarpaulin, with no perforations. Thus, the crabs would have no grip on the panel, and would have to reach across in order to pass it. Further, since the panel was non-perforated, there is an additional concern that it could interfere with the odour plume. Both a bait bag on the bottom of the pot and hanging bait box (Fig. 5) was applied, thus, there should be an odour trail to follow above and under the 50cm panel. However, the crabs could potentially lose the odour trail when moving from the mesh to the 50cm panel, which could in turn result in a reduced entry rate. Even though this study was not equipped to investigate the effect of the odour plume on search behaviour (for further discussion see discussion of methods 4.1.1), it is worth mentioning that most crabs attempted to enter the pots from an upstream position. More importantly, there was no difference between the control pot and the 50cm slippery-panel pot with regards to upstream or downstream entry attempts.

Majority of both small (CL $\leq$ 120mm) and large (CL > 120mm) crabs had exactly one entry attempt on the control pot, while most of the crabs had two or more entry attempts on the 50cm slippery-panel pot (Fig. 22). This is an indication of increased effort exerted by the crabs to enter the pot with a selection barrier. Although both small and large crabs displayed an increase in effort, the smaller crabs (CL $\leq$ 120mm) showed greater difference in number of attempts between the 50cm pot and control than the large crabs (CL > 120mm). This is likely linked to the entry rate, where the larger crabs have a higher probability of successfully entering (Table 3). The increase in number of attempts, and the increased mean duration for successful entries show that the crabs generally exert more effort attempting to enter the 50cm slippery-panel pot than the control pot. Which suggest an increased difficulty for entering the slippery-panel pot.

There was a difference in carapace orientation at successful entry between the control and the 50cm slippery-panel pot, for both small and large crabs (Fig. 23). The majority of both small (80%) and large crabs (76%) that entered the 50cm slippery-panel pot moved sideways, while for the control, the preferred way was sideways for the small crabs (46%) and forwards for the large crabs (50%) (Fig. 23). Thus, the addition of a slippery panel affects what direction the crabs move when entering the pot. The proportion of crabs moving forward and sideways in the control pot corresponds with the findings of Zhou and Shirley (1997b), where they observed 52.9% and 41.2% respectively in their study. Assuming the orientation observed by Zhou and Shirley (1997b) and in the control is the natural behaviour, the present findings shows that the RKC must change their entering behaviour (orientation) to be able to pass the selection barrier. As Davies et al. (2019) demonstrated the cognitive abilities to crabs (*Carcinus maenas)*, it would be interesting to see if this behaviour relating to entry orientation can be learned by experience or by observing other crabs entering. Retesting crabs that have managed to pass the slippery panel will answer the experience part. The crabs used in this study were naïve to the slippery panel but not to the control pot, as all crabs were caught from the field using square collapsible pots with one chamber.

When looking at what panel the crabs were in contact with during a successful entry, no clear difference was found between the control pot and the 50cm slippery-panel pot (Fig. 24). The crabs, independent of size, seemed to prefer entering the pot along the funnel edges, being in contact with panel B and a side panel, A or C (Fig. 13; Fig. 24). The proportion of crabs entering the pot in contact with panel A+B was higher than the proportion entering in contact with panel B+C. This is most likely an artefact due to the positioning of the pot in the tank. Panel A was the panel closest to the tank wall (Fig.13), thus, it was not surprising that a higher proportion entered the pot while in contact with panel A+B. Entering the pot by being only in contact with panel A was only observed once, which is not surprising given that panel A is a vertical wall and is therefore more challenging to climb than a slope, such as panel B. However, this does not mean the RKC is a poor climber. On the contrary, several individuals were observed on top of the pot, meaning they have climbed up along the entire side of the pot. Additionally, one crab was observed to climb almost all the way into the pot while hanging upside down from the ceiling.

4.2.3 Behaviour for successful and failed entry attempts on the 50cm slippery-panel pot

The findings of this study indicate that certain behavioural strategies provide an advantage in surpassing the 50cm slippery panel, when attempting to enter the experimental pot.

One of the behavioural strategies that provided an advantage was the use of the inner mesh wall (IMW) (Fig. 25). The majority (81%) of the crabs that successfully entered the 50cm slippery-panel pot used IMW, while only 2% of the crabs used IMW during their first failed entry attempt. An indication of how important the use of IMW can be to the success of an entry attempt. When positioned close to the inner funnel edge or on it, the crabs could reach the IMW with their walking legs. By holding on to the IMW with their walking legs, they could pull themselves over the inner funnel edge, into the main chamber. Without the use of IMW, there were no other way for the crab to pull themselves over the inner funnel edge. They would have to either leverage the mesh below the slippery panel in order to push themselves over the inner funnel edge or leverage the inner funnel edge with their claw to tip themselves over the edge. The two latter options seemed more difficult to achieve due to the slippery nature of the selection barrier. The reasoning behind a 50cm wide slippery panel was that the undersized crabs should not be able to push themselves over the inner funnel edge. By using the IMW, the crabs did not have to push themselves over the inner funnel edge, they could pull themselves over. Thus, I would attempt to improve the current slippery-panel design by adding a slippery panel to the IMW, which could hinder the crabs from utilizing this method to enter the pot.

Another behavioural strategy providing an advantage was the usage of the CUT (Fig. 15). The use of the cut was not as common as the use of IMW, and it seemed to have a different effect on the probability of entry success. The cut was more frequently used by the undersized crabs (54%) than for the legal sized crabs (14%) during successful entry attempts (Fig. 26), and from video observations it seemed to provide greater advantage to the smaller crabs. This suggests that the entry rate for undersized crabs would likely be lower if the CUT was not present, while the large crabs would be less affected. The use of the CUT usually provided stability to the crab when attempting to transverse the slippery panel. For the smaller crabs, its use seemed to make it easier for them to reach up to the inner funnel edge, and thereby increase their probability of entry. Although the cut occurred due to patchwork during this study and would not be included in the future pot design, it provided useful insight into how resourceful the crabs can be when attempting to enter a pot. Even though the cut was small compared to the funnel size, and was vertically orientated, several crabs managed to find it and use it to their advantage. This observation suggests that if a slippery panel were to be used in the pot fishery, the panel should consist of a single seamless piece, and not be put together by several panel, given that edges, cuts, rifts, or damage to the slippery panel are likely to compromise the size selective properties of the panel.

A third behavioural strategy that provided an advantage was the carapace orientation. When comparing the carapace orientation between successful and failed entry attempt on the 50cm slippery-panel pot, for the same individuals, a significant difference was found (Fisher's Exact, $p = 0.0056$). Most crabs (86%) moved sideways for the successful entries while no crabs moved forward (Fig. 27). For the failed attempts, only 35.7% moved sideways and 42.9% moved forwards (Fig. 27). This suggests that a crab moving sideways is more likely to succeed at entering the pot than a crab moving forwards. It also looks like the crabs change their carapace orientation on the following attempts, after a failed attempt (Fig. 27). Thus, learning might very well be involved (Davies et al. 2019). This is further supported by experiments done on a Varunidae crab (*Chasmagnathus granulatus),* which showed the crabs could be learned passive avoidance by shock, an avoidance that persisted for 3 hours (Denti et al. 1988).

Even though most crabs successfully entered the pot while in contact with Panel A+B (57%) and most crabs that failed to enter the pot were in contact with panel B (57%) (Fig. 28). No significant relationship was found when comparing crab positioning between successful/failed entry attempt (Fisher's Exact, $p = 0.4071$). This indicates that the positioning in the funnel does not have a significant impact on the probability of successful entry. It would be preferable to acquire more observations in order to arrive at a more robust conclusion, since only 14 observations were used for the statistical test. However, seen in relation with the other behavioural results in this study, it seems reasonable to conclude that position in the funnel have less impact on the probability of entry, and that its rather the use of IMW, CUT and carapace orientation that is the determining behavioural factors.

4.2.4 Two-chamber pot

As predicted, the addition of a baited bottom chamber equipped with circular escape openings was highly efficient in allowing undersized (CL < 130mm) crabs to escape the pot. While most undersized crabs (85%) moved from the main chamber to the bottom chamber, none of the five legal sized crabs managed to descend (Fig. 29). Resultingly, CL has a significant effect on the probability of decent (model 3). This corresponds with previous studies, which documented that trapped RKC are very likely to use escape openings of various diameters, if they fit trough (130-200mm) (Salthaug and Furevik 2004; Jørgensen et al. 2017). Furthermore, RKC has been observed to both enter and exit via the escape openings (Siikavuopio et al. 2018). While these studies already show that RKC is very likely to take advantage of escape openings, there was a distinct difference in how the escape openings were positioned in these studies and the present study. Common for the three studies, the escape openings were positioned vertically in a pot wall. So, a crab encountering the escape opening would be able to walk through it. In this study however, the escape openings were situated horizontally in the floor of the main chamber. Here, the crabs would have to drop down into the bottom chamber in order to leave the main chamber via an escape opening. With a distance of 37cm from the escape openings to the tank bottom (Fig. 5), no crab was able to reach the bottom before putting their body through the escape opening. Both undersized and legal sized crabs were observed to extend their walking legs and/or claws into the escape openings, reaching into the bottom chamber. Eventually, they either moved away from the escape opening, or moved down to the bottom chamber via the escape opening.

Once descended into the bottom chamber, no crab managed to ascend to the main chamber again. Even though the crabs frequently climbed on the walls of the bottom chamber, and sometimes in the ceiling. In the initial design used in the pilot study, crabs descended and ascended via the escape openings. Then the escape openings were positioned along the pot wall, and crabs could use the wall to reach and move through the escape openings. However, in the design used in this study, the escape openings were relatively far away from the pot wall. Thus, the crabs were unable to reach the escape opening from the pot wall. This suggests that the repositioning of the escape openings from along the walls to a more centred position (Fig. 5) was successful.

Crabs of all sizes attempted to reach the bait bag in the bottom chamber through the main chamber floor by inserting their claws through the mesh, but quickly stopped as they could not fit their claw through the small mesh size (1x1 cm) (Fig. 5). This is coherent with observations made by Zhou and Shirley (1997a), where the crabs would move more actively around if they could not insert their claws through the mesh, compared to it if they could.

There was only one large crab (CL > 13cm) in each group. These crabs were observed attempting to reach the bait bag by inserting their claws through the escape openings. Even though they had numerous attempts, they never succeeded. While attempting to reach, the crabs would be blocking the escape opening they were reaching through. The crabs did however not remain on top of the escape openings when not attempting to reach the bait bag. Thus, blockage was only observed when large crabs attempted to reach for the bait bag, or when undersized crabs (CL < 130mm) attempted to move through. Nonetheless, blockage might become a problem at higher densities within in the main chamber as larger crabs have been observed to block escape openings for long periods (Jørgensen et al. 2017).

As this study had a density of 13-15 crabs in the main chamber, for all trials. Notably, the observations and conclusions drawn regarding descension and ascension are dependent of crab density in main and bottom chamber. Although a density of 15 crabs was necessary to allow for observations of individual's behaviour within the pot, and the availability of crabs was limited, catches in commercial fishery are usually higher. It is not unlikely that the proportion of undersized crabs descending to the bottom chamber will decrease with an increasing density in main chamber and bottom chamber. As the bottom chamber is smaller than the upper chamber, it will eventually become full as density increases. Additionally, with increasing density in main chamber, it will likely be more difficult for individual crabs to access the escape openings. Thus, based on observations in this study, I expect the bottom chamber to be highly effective at allowing undersized crabs to escape, until the crab density in pot reaches a certain level. Although not observed at the low density in this study, a concern is that crabs may climb on each other in order to ascend back into the main chamber. This is, however, not likely until a high density in the bottom chamber is reached.

4.3 Concluding remarks

The slippery-panel design had a size selective effect when a panel width of 50cm was used, where the probability of entry increased with increasing CL. However, from the modelled entry rate and observations from video recordings, it was clear that behaviour in the funnel played a major role in the probability of entry. My findings indicate that the use of the inner mesh wall (IMW), a cut in the slippery panel (CUT), or the carapace orientation could increase the probability of entry, for all crab sizes present in the experiment. The addition of a slippery panel to a standard LH-pot affected the RKC behaviour in the funnel, as it increased the entry duration and effort required. Based on these findings, I believe the slippery-panel design has potential, but require further modifications in order to improve its size selectivity.

The results from the escape experiment showed that the two-chamber design was highly effective at low density. Majority of the undersized crabs descended into the bottom chamber, while none of the large individuals descended. Furthermore, none of the small crabs succeeded at ascending back up to the main chamber. It is imperative to note that the effectiveness of the two-chamber design was tested with low crab densities in main chamber. Therefore, I suspect the design will have reduced effectiveness of sorting out undersized crabs with increasing densities. This is based on the escape opening being positioned in the bottom of the main chamber, and the limited volume of the bottom chamber. Thus, at higher densities, I expect the efficiency of the slippery-panel design to be superior to the two-chamber design.

4.4 Recommendation for future study

The findings of this study showed promise for a slippery-panel design with a 50cm panel width. However, the design requires modifications to improve the size selectivity, as undersized individuals succeeded at entering. The usage of the inner mesh wall (IMW) seemed to provide an increased probability of successful entry, for all CL. Therefore, I recommend adding a slippery panel to the IMW. This way, the crabs will not be able to use the IMW to pull themselves over the funnel edge, forcing them to push themselves over the edge, or leverage the inner funnel edge. The addition of a slippery panel to the IMW will likely affect the entry strategy of the crabs, as most successful entries utilized the IMW. I suggest investigating potentially new strategies after the addition of the new panel, to then optimize the slippery panel width accordingly. Furthermore, I recommend creating the slippery panels of one whole piece of material and minimizing the presence potential traction areas. This is based on the observations of crabs utilizing a cut in the slippery panel, where several of them used this construction flaw to their advantage, indicating that they can use small areas of traction to transverse the slippery panel, and that they are skilled at locating and taking advantage of structures.

The results from the escape experiment displayed a high escape rate for the undersized crabs in the two-chamber design. However, the escape rate was investigated at low densities, of 15 individuals. Thus, future research should investigate how the escape rate is affected by increasing density and uncover the maximum number of crabs which can escape into the bottom chamber. Furthermore, since the crabs were positioned inside the two-chamber pot during this study, the entry rate of the two-chamber design is unknown. As the two-chamber pot has an additional chamber beneath the main chamber it is possible that the design alterations can affect search behaviour and entry rate. When a crab encounters the two-chamber design, it will encounter the bottom chamber at seabed level, and therefore a net wall instead of a net ramp. Thus, it could be more difficult for the crabs to start a successful vertical search when encountering the two-chamber pot (Stiansen et al. 2010). Based on this, future research should also include an investigation of the entry rate of the two-chamber pot.

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6. Appendices

Appendix 1

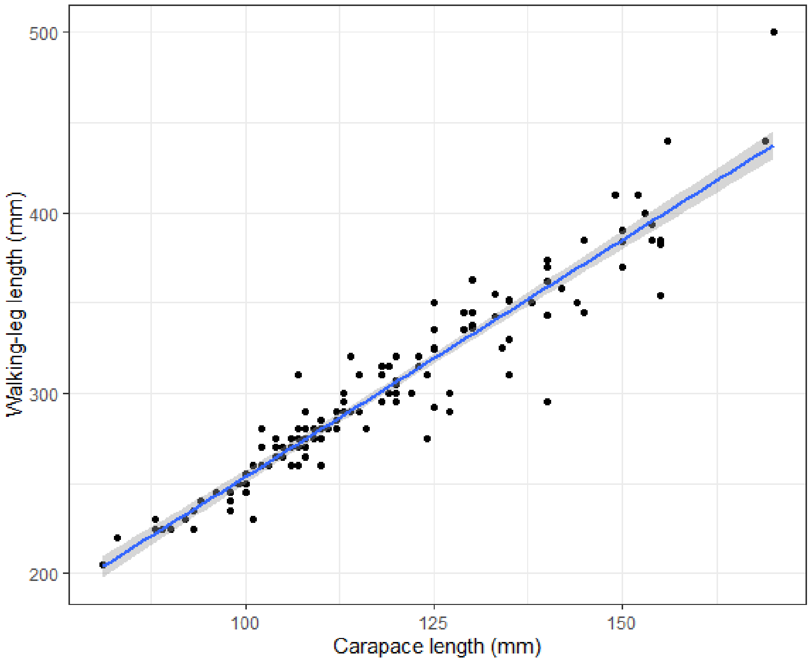
Measurements for all crabs included in study, measured in mm. H2 = second right leg measured, V2 = second left leg measured. Individuals with V2 are marked in grey.

ID	Group	Carapace Length	Carapace Width	Leg Length	Leg measured
101	1	116	136	280	H2
102	1	113	133	295	H2
103	1	113	133	300	H2
104	1	114	134	320	H2
105	1	110	129	275	H2
106	1	107	138	260	H2
107	1	106	125	275	H2
108	1	102	119	260	H2
109	1	105	126	265	H2
110	1	110	134	285	H2
111	1	102	120	260	H2
112	1	104	121	275	H2
113	1	94	110	240	H2
114	1	101	118	260	H2
115	1	129	156	335	H2
201	2	113	132	290	H2
202	2	124	147	310	H2
203	2	110	129	280	H2
204	2	122	143	300	H2
205	2	124	142	275	H2
206	2	104	123	270	H2
207	2	108	128	275	H2
208	2	106	125	270	H2
209	2	92	107	230	H2
210	2	104	126	265	H2
211	2	108	126	280	H2
212	2	98	112	240	H2
213	2	110	124	275	H2
214	2	107	129	270	H2
215	2	153	195	400	H2
301	3	118	138	315	H2
302	3	107	137	310	H2
303	3	108	131	270	H2
304	3	113	126	290	H2
305	3	119	144	300	H2
306	3	102	118	270	H2
307	3	100	118	250	H2
308	3	103	122	260	H2
309	3	109	127	280	H2
310	3	106	123	260	H2
311	3	100	117	245	H2

312	3	102	116	280	H2
313	3	109	126	275	H2
314	3	109	129	280	H2
315	3	156	190	440	H2
401	4	108	128	265	H2
402	4	119	143	315	H2
403	4	109	129	275	H2
404	4	120	139	295	H2
405	4	114	134	290	H2
406	4	98	117	245	H2
407	4	93	105	235	H2
408	4	88	99	225	H2
409	4	105	124	270	H2
410	4	98	113	245	H2
411	4	102	116	270	H2
412	4	107	123	275	H2
413	4	101	121	260	H2
414	4	112	130	285	H2
415	4	170	215	500	H2
501	5	112	132	290	H2
502	5	119	137	315	H2
503	5	118	143	310	H2
504	5	115	139	310	H2
505	5	111	132	280	H2
506	5	96	115	245	H2
507	5	99	112	250	H2
508	5	101	116	230	H2
509	5	81	93	205	H2
510	5	88	100	230	H2
511	5	110	124	260	H2
512	5	89	102	225	H2
513	5	104	120	265	H2
514	5	107	124	280	H2
515	5	149	184	410	V2
601	6	108	125	290	H2
602	6	118	140	295	H2
603	6	115	130	290	H2
604	6	111	128	280	H2
605	6	120	141	320	H2
606	6	100	113	255	H2
607	6	98	110	235	H2
608	6	83	95	220	H2
609	6	93	103	225	H2
610	6	90	105	225	H2
611	6	98	111	245	H2
612	6	100	116	255	H2
613	6	112	126	280	H2
614	6	105	124	270	H2

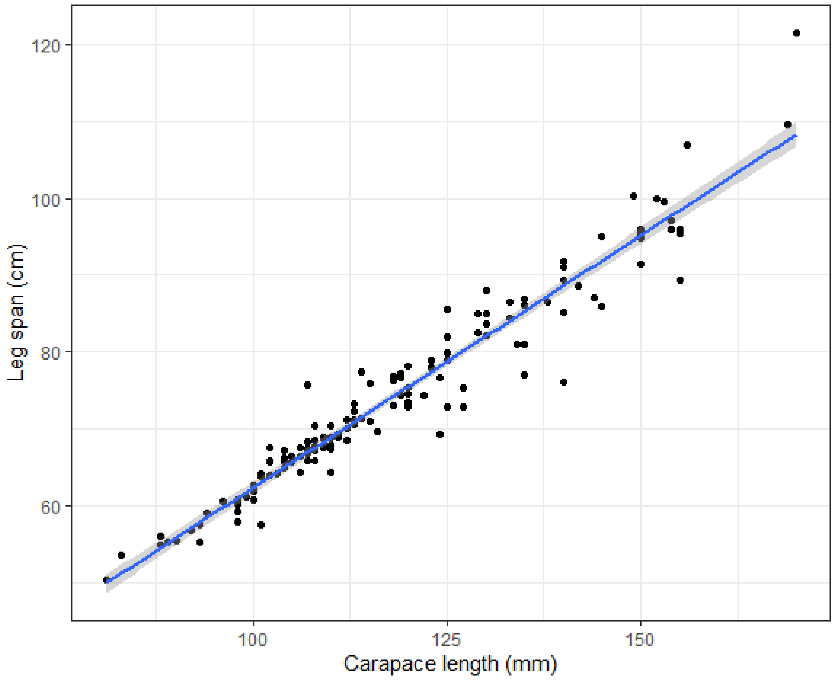
615	6	169	215	440	H2
701	7	155	185	354	H2
702	7	130	160	345	H2
703	7	150	185	384	H2
704	7	127	149	290	H2
705	7	140	170	374	H2
706	7	135	160	351	H2
707	7	155	190	382	H2
708	7	145	180	385	H2
709	7	125	145	292	H2
710	7	144	170	350	H2
711	7	154	190	385	H2
712	7	154	185	393	H2
713	7	142	170	358	V2
714	7	140	165	343	H2
715	7	134	160	325	H2
816	8	152	180	410	H2
817	8	150	180	384	H2
818	8	145	170	345	H2
819	8	140	170	362	H2
820	8	135	165	352	H2
821	8	129	160	345	H2
822	8	140	170	295	H2
823	8	133	160	342	V2
824	8	125	155	350	H2
825	8	155	190	385	H2
826	8	138	165	350	H2
827	8	150	180	390	H2
828	8	133	155	355	H2
829	8	150	175	370	H2
830	8	140	170	370	H2
931	9	125	150	324	H2
932	9	135	150	330	H2
933	9	123	150	315	H2
934	9	123	150	320	H2
935	9	135	150	310	H2
936	9	120	140	307	H2
937	9	120	145	300	H2
938	9	120	143	305	H2
939	9	125	150	335	H2
940	9	125	140	325	H2
941	9	127	154	300	H2
942	9	130	155	363	H2
943	9	130	160	338	H2
944	9	120	145	295	H2
945	9	133	160	342	H2

Appendix 2



The relationship between Carapace length (mm) and Walking-leg length (mm) was found to be highly correlated using a Pearson's product-moment test (r = 0.94, n = 135, p = 2.2e-16).

Appendix 3



The relationship between Carapace length (mm) and Leg span (cm) was found to be highly correlated using a Pearson's product-moment test (r = 0.97, n = 135, p = 2.2e-16). Leg span was estimated by multiplying measured leg length by two and adding measured Carapace width, which gives a relatively precise estimation of max lateral range.

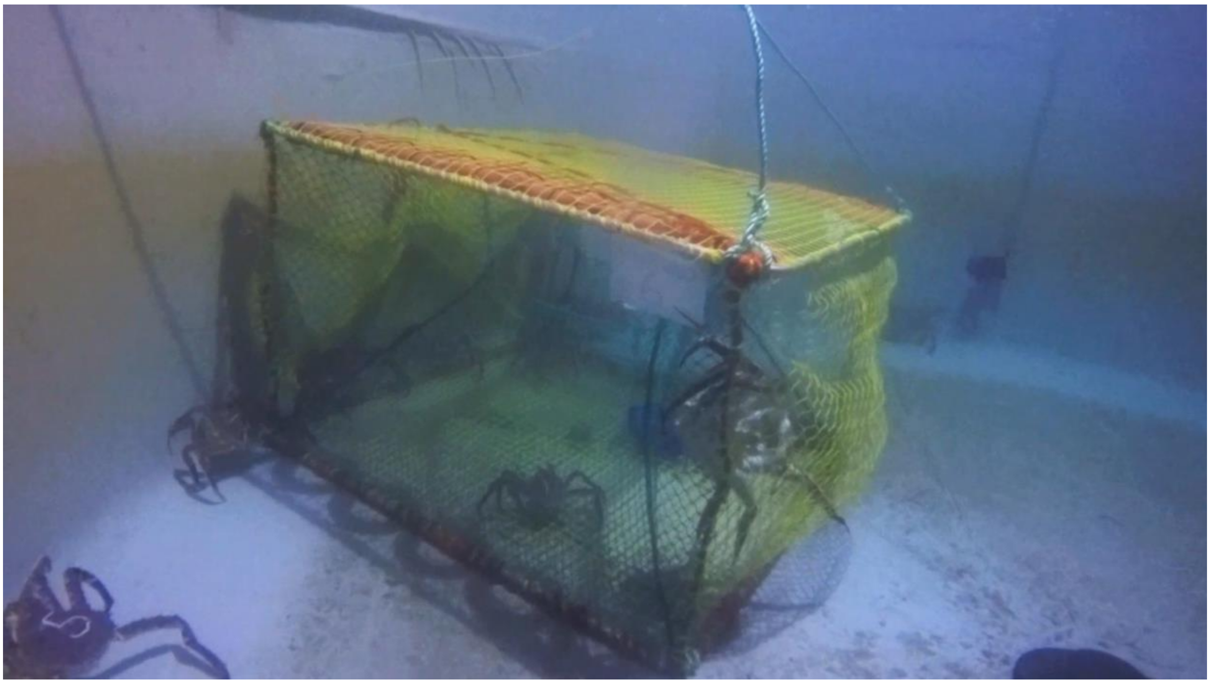
Appendix 4

Benthic 3 underwater housing kit from Group B Distribution Inc and GoPro hero 5

Appendix 5

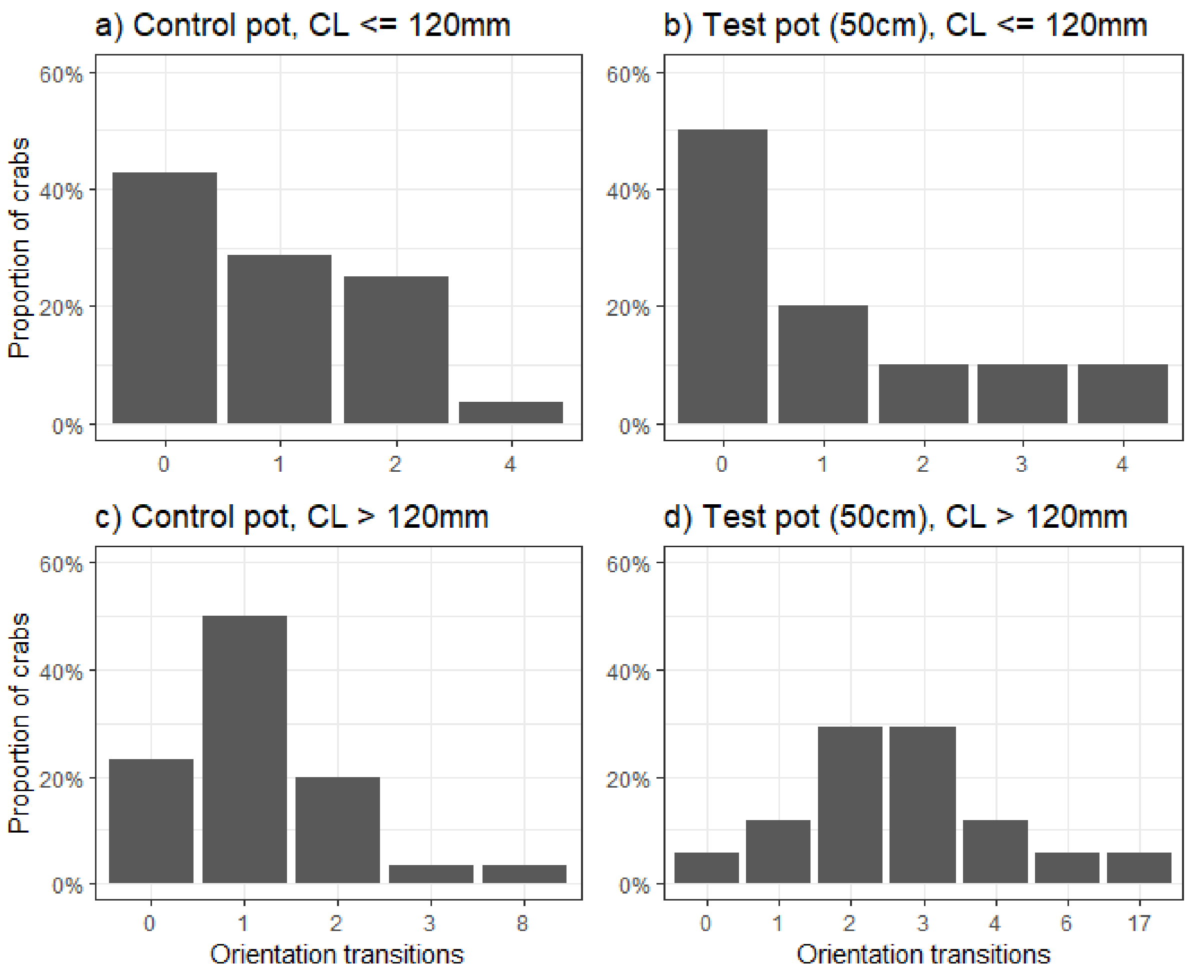
Field of view from downstream camera

Appendix 6



Field of view from upstream camera

Appendix 7



Orientation transitions represents how many times a crab changes between the different Carapace orientation (CFWD, COBLQ, CSIDE; Table 2). Where 0 transitions mean the crab entered the pot without changing carapace orientation. Observations per pot; a) n = 28, b) n = 10, c) n = 36, d) n = 17