Detection probability of Antarctic minke whales: analyses of the BT mode experiments conducted on the IWC-SOWER cruises 2005/06 – 2007/08

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ABSTRACT

IWC sightings surveys to obtain abundance estimates of cetaceans have taken place in the Antarctic since 1978/79. In order to interpret the minke whale abundance from these surveys and to trial different search protocols for future cruises, Buckland-Turnock (BT) search mode experiments were conducted during the IWC-SOWER 2005/06, 2006/07 and 2007/08 cruises. BT search mode is a particular configuration of a double-observer survey. Double-observer methods combine aspects of mark-recapture and distance sampling to estimate density without assuming detection is certain on the trackline.

In BT mode, observers are generally located on two separate platforms and act as either a 'primary' or 'tracker' observer. The tracker searches far ahead of the vessel to detect animals before the primary, thus setting up trials for the primary; a successful trial is one in which the primary detects the same animal. Analysis of these trials allows the probability of detection for the primary to be estimated. Two configurations of BT mode were implemented on the SOWER cruises; BT-NSP mode and BT-option 2. Normal standard passing (NSP) mode is a standard search mode for SOWER vessels and in BT-NSP mode, the observer located on the barrel became the primary and searched as usual in NSP mode with 7x50 binoculars; the observers on the upper bridge became the tracker and used big eye binoculars mounted on the upper bridge. Thus, the probability of detection for the observer in the barrel can be estimated which can inform interpretations of abundance estimates of SOWER data. For BT-NSP mode, the estimates of detection probability on the trackline for the observer in the barrel ranged between 0.42 (cv=41%) to 0.69 (cv=23%) for the different years and combinations of data and models. In BT-option 2, the observer on the barrel (searching with 7x50 binoculars) acted as tracker and the observer on the independent observer (IO) platform acted as the primary (searching with naked eye). For this configuration, the estimates of primary detection probability on the trackline were 0.25 (cv=59%) and 0.32 (cv=49%) for two different models.

KEYWORDS: SOUTHERN HEMISPHERE, SOWER, MINKE WHALES, *g*(0), MARK_RECAPTURE

INTRODUCTION

Sightings surveys have taken place in the Antarctic under the auspices of the International Whaling Commission (IWC) every austral summer since 1978/79 and there are now three circumpolar (CP) sets of surveys. Abundance estimates, obtained using conventional line transect distance sampling (DS) methods (Buckland *et al*. 2001), have indicated an appreciable decline in minke whale abundance between CP II and CP III (Branch and Butterworth, 2001). Two key assumptions of conventional distance sampling (DS) methods are that animals on the trackline are certain to be seen (denoted by *g*(0)=1) and that they are seen before they have moved in response to the vessel. To ensure these assumptions were valid using standard Southern Ocean Whale and Ecosystem Research (SOWER) search modes, observers searched with 7x50 binoculars and there were observers searching from either two or three different platforms on the ship depending on the choice of selected survey mode. In conventional DS analyses of the SOWER data (Branch and Butterworth, 2001), sightings from all platforms were combined and treated as though they were made from a single platform. Despite these measures, differences in cetacean cue size and behaviour may still result in DS assumptions being violated. It has been suggested that estimates of g(0) from standard SOWER search modes may be positively biased because, although observers were acting independently, they tended to search the same area of the sea and the resulting dependence of detection probability on unmodelled variables can induce correlation in the detection probabilities (IWC, 2005). However, methodology combining both mark-recapture and distance sampling (MRDS) has been developed to overcome these difficulties (see Laake and Borchers, 2004, for an overview). In particular, MRDS methods allow the probability of detection on the tracklineto be estimated, and hence density and abundance, can be estimated rather than assuming *g*(0) is one.

A series of experiments using MRDS methods were conducted on the 2005/06, 2006/07 and 2007/08 IWC SOWER cruises in order to:
a) help interpret abundance estimates obtained from previous analyses of data from SOWER cruises by providing independent estimates of detection probability and,
b) assess alternative search protocols that could be used on future cruises.

The particular implementation used on the SOWER vessels was the Buckland Turnock (BT) method (Buckland and Turnock, 1992). In BT mode, observers are generally located on two separate platforms and act as either 'tracker' or 'primary' observers. The tracker scans a region sufficiently far ahead of the vessel that animals are unlikely to have reacted to the vessel's presence before being detected. Animals detected in this region are then followed by the tracker. The primary acts independently of the tracker searching closer to the vessel and if the primary subsequently detects the same group as the tracker, this is termed a duplicate sighting. With this setup, duplicates can only occur if the tracker sees the animal first because the tracker is generally aware of any sightings made by the primary. Sightings made by the tracker thus serve to set up binary trials for observations made by the primary (the outcome of each

trial is either 'seen' or 'not seen' by the primary). Analysis of these trials and duplicate sightings allows the probability of an animal being detected by the primary to be estimated.

BT MODE IMPLEMENTATION ON SOWER VESSELS

Standard SOWER search modes

Prior to 2005/06, minke whale research was conducted on the SOWER vessels using two principal search modes; closing mode and passing with independent observer (IO) mode (Table 1a). In closing mode, observers were located on the barrel and upper bridge and sightings were approached in order to determine species and school size more accurately. In IO mode, observers were located on the barrel, upper bridge and the independent observer platform (IOP) and the vessel did not deviate from the trackline. Normal standard passing (NSP) mode was identical to IO mode except that the independent observer was not in place. All observers searched with handheld 7x50 binoculars and, as a consequence, there was no separation of search areas. The observers in the barrel contributed nearly half of all sightings made during these search modes and the upper bridge contributed nearly one third (Table 2). During survey in IO mode, the IOP contributed nearly 30% of sightings.

BT mode searching

In 2005/06, the BT mode experiment was conducted in both NSP and IO mode. In BT-NSP mode, the observers in the barrel acted as usual in NSP mode (i.e searching with 7x50 binoculars) but were considered to be the primary observers. One observer on the upper bridge acted as the tracker and, to achieve a separation of search areas, used higher powered (x25) big eye binoculars (BE). Although the upper bridge was the lowest platform, it was chosen as the tracker platform because it was the only practical location where the BE could be installed and isolated from ship vibration (Ensor *et al*. 2006). The other upper bridge observers assisted with tracking and duplicate identification. In BT-IO mode, an observer on the IOP operated as an additional primary observer but acted independently of the observer in the barrel and *vice versa*. The intention was to conduct most of the BT experiment in IO mode to be comparable with the standard SOWER methodology and thus estimate a detection probability for both the observers in the barrel and IOP. However, difficulties were experienced conducting BT trials during IO search mode due to the additional data recording, tracking and duplicate assessment related to the BE sightings and so the majority of the BT mode experiment was conducted in BT-NSP mode (Ensor *et al*. 2006).

BT-NSP mode was again used in 2006/07. The BE were larger, heavier and of higher optic quality than those used previously and so thus could be used in a greater range of weather conditions (Ensor *et al*. 2007). The protocol was also modified so that closure to all minke sightings initially detected by the BE was attempted after tracking and when the sightings were judged to be abeam of the vessel (and therefore no longer able to be detected by the primary observers). The purpose was to obtain accurate school size information of BE sightings.

A trial of BT-option 2 was carried out in 2006/07 and this involved a different platform configuration to that of BT-NSP. In BT-option 2, observers in the barrel acted as trackers and searched with 7x50 binoculars. The primary observers were located on the IOP and searched with naked eye. The upper bridge observers assisted with tracking and duplicate identification. BT-option 2 was implemented as a standard search mode for the second half of the 2007/08 cruise to evaluate its utility as a potential replacement for IO mode.

Configuration of the three platforms for all the search modes is shown in Table 1.

ANALYSIS METHOD

Detection function

The analysis is based on methodology developed by Borchers *et al* (1998; 2006). In BT mode, the role of the tracker is to generate detections of animals before they have responded to the vessel. Estimation of the intercept of the detection function for the primary observer is then conditioned on these detections. The detections by the tracker serve as a set of binary trials in which success corresponds to detection by the primary. The probability that an animal at a given perpendicular distance y is detected by the primary, denoted by $p_1(y)$, is modelled as a logistic function;

$$p_1(\mathrm{y}) = \frac{\exp\{\beta_0 + \beta_1 y\}}{1 + \exp\{\beta_0 + \beta_1 y\}} \qquad (1)$$

where β_0 and β_1 represent the parameters to be estimated. Thus, setting y=0 will provide an estimate of the detection function intercept. We refer to this as the mark-recapture (MR) model. The shape of the detection function for the primary is based on a conventional distance sampling (DS) detection function obtained from the primary perpendicular distances (the DS model, see later).

With the BT-NSP configuration, an estimate of the detection probability for the observers in the barrel can be obtained and since the primary observers were acting in BT-NSP mode as they would in standard SOWER search modes, this will provide an insight into the abundance estimates obtained from SOWER data. BT-option 2, will provide an estimate of detection probability for the observers in the IOP searching with naked eye, however, since this is not a standard SOWER survey protocol, it will not help with interpretation of past data.

Independence of detections

Although the primary observers act independently of the trackers, the detection probabilities can still be correlated, for example because they both preferentially see large schools. While school size (and all other recorded variables thought to affect detection) can be incorporated into the model, dependence of detection probability on unmodelled variables can still induce correlation in detection probabilities (termed unmodelled heterogeneity). Laake and Borchers (2004) and Borchers *et al*. (2006) developed an estimator based on the assumption that detections were independent at zero perpendicular distance only (called a point independence model). This estimator was more robust to violation of the assumption of no unmodelled heterogeneity than a full independence model which assumed that detections were independent at all distances. The point independence model essentially uses the shape of the conventional DS detection function estimated from the DS model and obtains the intercept of this function from the MR model (eqn. 1). The full independence model uses only the MR model to estimate both the intercept and the shape of the detection function. When animals move in response to the vessel between detection by the tracker and detection by the primary, the effects of unmodelled heterogeneity off the trackline and responsive movement cannot be separated (Cañadas *et al*., 2004; Borchers *et al*. 2006). Therefore, if animal movement is anticipated, the DS model is unreliable and a full independence model is preferable.

Estimating abundance

Although we do not do so here, the estimated number of animals in the study region, $\hat{N}_G$, can be estimated using a Horvitz-Thompson-like estimator

$$\hat{N}_G = \frac{A}{2wL}\sum_{i=1}^{n_1}\frac{s_i}{\hat{E}[p_1(y)]}$$

where A is the size of the study region, w is the truncation distance, L is the total search effort, n_1 is the number of groups detected by the primary observer and s_i is the size of the group i. The expected value of $p_1(y)$, $\hat{E}[p_1(y)]$ is given by

$$\hat{E}[p_1(y)] = \int_0^w \hat{p}_1(y)\pi(y)\,dy$$

The probability density function of perpendicular distances, π(y), is assumed known (usually $\pi(y) = 1/w$ for line transect surveys). If covariates Z are included in the model to model heterogeneity, in addition to perpendicular distance, then $\hat{E}[p_1(y,Z)]$ can be obtained by averaging over all covariates using appropriate weights.

RESULTS

Search effort

In order to maximise the sighting rate (and hence the number of duplicate detections) in 2005/06 and 2007/08, the BT experiments were conducted in the vicinity of the ice edge, a flexible cruise track was adopted and regions with higher sightings rates were covered more than once (Figure 1; Ensor *et al*. 2007). In 2007/08, a pre-defined cruise track was used. In BT-NSP mode, 1,385 nm of trackline were covered in 2005/06 and 1,196 nm in 2006/07. In BT-option 2 mode, 275 nm of trackline were covered in 2006/07 and 564 nm in 2007/08.

Search regions of observers

Search regions are an important part of the BT method and ideally the search regions of the two observers should be separated. Examining the angles and radial distances to sightings of all species gives an insight into the search regions for the different platforms. Angle and distance estimation experiments were performed to assess any bias in the sighting angles and radial distances recorded from the various platforms. Analyses indicated there was significant bias in a few cases and the recorded angles and distances were corrected using the bias factors shown in Table 3.

In BT-NSP mode, the trackers were instructed to search an area no more than 45° either side the trackline and ahead of the area searched by the primary who searched as usual (IWC, 2005). Figure 3 showed that the BE observer clearly searched within 45° of the trackline, although the distribution of sighting angles indicated that they appeared to have concentrated more off to the sides and not so much on the trackline. The radial distance distribution and Figure 4 showed that there was considerable overlap between the region searched by the tracker and the region searched by the primary.

In BT-option 2, the trackers were instructed to focus their searching far ahead of the vessel and up to 60° either side of the trackline and the primary observers searched with naked eye up to 90° either side of the trackline (IWC, 2006). Figures 3c and 3d show that there was much more of a separation of search regions since the range the primary observers were able to see was necessarily limited due to searching with naked eye.

Responsive movement

Figure 2 shows the perpendicular distances of duplicate sightings at the time they were initially detected by the tracker and then subsequently by the primary. One needs to be cautious about interpreting responsive movement from this figure because animals moving towards the vessel are more likely to become duplicates because they become more detectable to the primary observers. Such animals are therefore more likely to appear in the figure than animals moving away from the vessel. Thus, observing more duplicates moving towards, rather than away from, the vessel is not necessarily an indication of attractive movement and this information can

only generally provide an indication of responsive movement if the reaction is severe. Errors in sighting angles and radial distances can also mask any reactions. In this case, Figure 2 does not suggest much, if any, responsive movement.

School size

Errors in school size can have an impact on the abundance estimate. Borchers *et al*. (1998) estimated a correction factor for school sizes recorded by primary observers using the school size estimates from duplicate detections only; in that analysis, trackers and primary observers recorded school size independently and trackers were thought to estimate school size more accurately. In the SOWER surveys the 'best' estimate (usually made by observer in the barrel) is assigned to both records in the duplicate pair thus a correction factor similar to that of Borchers *et al*. (1998) can not be estimated. Dedicated experiments to assess school size error were conducted during the 2006/07 survey but the results from that experiment have not been included in this analysis. However, as noted previously, the search protocol for BT-NSP mode was changed in 2006/07 so that all minke whale sightings made by the BE were approached to obtain more accurate school size estimates and 85% of these sightings had confirmed school sizes. Table 6 shows that approximately half of all animals detected were either single animals or in groups of two, but the proportion of single animals were substantially lower in 2006/07, when school sizes were confirmed, than in 2005/06.

Detection functions

To estimate the detection function, sightings of minke whale schools (species code 04), 'undetermined minke' (91) and 'like minke' (39) have been used. These are all referred to as minke whales (see table 4 for the numbers in each species code). Only sightings classified as 'definite' duplicates were considered to be duplicates. Table 5 shows the number of minke whale sightings recorded by the different observers. In 2005/06 BT-NSP mode, there were 41 tracker sightings of minke whale and the primary saw 21 of them. In 2006/07 BT-NSP mode, there were 65 tracker sightings and 31 duplicate sightings. In BT-option 2, there were 101 tracker sightings of minke whales schools and 27 duplicates. In 2007/08, BT-option 2 mode generated 10 tracker sightings and only 2 duplicates - too few to be able to fit the models reliably and so this data is not pursued further.

The explanatory variables considered, in addition to perpendicular distance, were school size, weather code, Beaufort sea state and sightability (a subjective impression of the conditions for spotting whales). Akaike's Information Criterion (AIC, Akaike 1973) and χ^2 goodness of fit tests were used to choose which variables were included.

As mentioned already, an important consideration during analysis is whether to fit a point or full independence model. If responsive movement occurs then a full independence model is preferable, otherwise a point independence model is preferable given the strong assumption in the full independence model that detections are independent at all distances. Although Figure 2 does not suggest much, if any, responsive movement both point and full independence models have been fitted. A point independence model requires that both a DS model and an MR model are specified. For the DS model, both hazard and half-normal forms were considered but the hazard rate model was preferable in all cases. The most important explanatory variable was school size and this was included in nearly all models either as a factor or non-factor variable. Beaufort sea state was also included in two models. The chosen models are given in Table 7 and the detection functions are shown in Figure 5.

Detection probability of the primary observer

Using the point independence model, estimates of probability of detection on the trackline for the primary observer were for BT-NSP mode, 0.69 (cv=23%) in 2005/06; and 0.51 (cv=21%) in 2006/07. For BT-option 2 it was 0.31 (cv=49%). The same estimates from the full independence model were very similar, if slightly lower (and coefficients of variation higher) than estimates from the point independence model (Table 7).

The estimated average probabilities of detection for the primary observer (averaged over all explanatory variables including perpendicular distance) are also given in Table 7 and these are higher for the full independence models than for the point independence models, as would be expected. These average probabilities of detection are determined from the DS model assuming point independence and this function tends to decline more rapidly as perpendicular distance increases than the MR model on which the full independence model is based (Figure 5).

School size, s, was an important factor affecting detectability and was incorporated the MR model as follows:

$$p_1(y,s) = \frac{\exp\{\beta_0 + \beta_1 y + \beta_2 s\}}{1 + \exp\{\beta_0 + \beta_1 y + \beta_2 s\}}$$

By substituting distance y=0, the probability of detection on the trackline for different school sizes was estimated for the point and full independence models fitted to the 2006/07 BT-NSP data and the BT-option 2 data (Table 8). Using the model fitted to the 2006/07 BT-NSP data where school size was fitted as a continuous variable, the probability of detection on the trackline for solitary animals was 0.46 (cv=28%). Fitting school size as a factor variable, the probability of detecting a solitary animal was 0.29 (cv=38%). The maximum group size recorded in BT-NSP model was 40 animals. Using the model fitted to the 2006/07 BT-option 2 data, the estimated probability of detection on the trackline for solitary animals was 0.13 (cv=66%) (Fig. 6b). The maximum school size recorded in BT-option 2 mode was 29 animals for which the detection probability was 0.88 (cv=9%).

Of interest in the analyses of SOWER data was the detectability of single animals compared to animals in groups of two or more. To investigate this, an additional factor variable which indicated whether the school size was one or more than one (called SizeOne) was included in the point independence model for the BT-NSP mode data. The results of this model clearly indicated that there was a difference between single animals and groups of animals (Fig. 7a). A further model was fitted which included Beaufort sea state (in

this analysis divided into two factor levels, ≤3 and >3). This had no effect on the detection probability when included as a main effect in the model (along with size and SizeOne), but did have an effect when the interaction term between Beaufort sea state and SizeOne was added (Fig. 7b).

DISCUSSION AND CONCLUSIONS

The main aims for performing the BT mode experiments were to obtain an independent estimate of the probability of detection on the trackline for the different platforms used on the SOWER vessels and to evaluate BT mode as a potential survey methodology for future SOWER cruises. Independent estimates of the probability of detection on the trackline, in particular for the barrel and IOP, would help interpretation of minke whale abundance estimates obtained from analyses of SOWER survey data. The probability of detection on the trackline for the barrel was estimated to be 0.69 (cv=23%) and 0.66 (cv=30%) in 2005/06 for the point and full independence models, respectively. In 2006/07, these probabilities were slightly lower; 0.51 (cv=21%) and 0.42 (cv=41%), respectively. This inter-year difference may be a reflection of the better weather conditions experienced in 2005/06 and the higher quality BE binoculars used in 2006/07 which facilitated survey in poorer weather conditions than in the trials performed the previous year. It was found to be infeasible to implement BT-IO mode and so an estimate for the IOP, searching as per standard SOWER IO mode protocol, could not be obtained.

In BT-option 2, for the 2006/07 trials, the probability of detection for the IO searching with naked eye (primary) was estimated to be 0.31 (cv=49%) and 0.25 (cv=59%) for the point and full independence models, respectively. The evaluation of BT-option 2 during 2006/07 and 2007/08 as a potential survey method for future cruises identified distinct practical advantages over standard IO mode survey. Notwithstanding its success as an alternate survey method for minke whales, tracking and assessment of duplicate status for large, baleen whales was less problematic in BT-option 2 mode. As large, baleen whale cues are potentially detected at long radial distances, the duration of tracks can be long and assessment of duplicate status is difficult in IO mode. Due to the substantial increase in sighting rates for large baleen whales (mainly humpback whales), this important aspect of IO mode is likely to become more problematic in the future (Ensor *et al*. 2008) .

School size is an important factor affecting detectability, and the probability of detection on the trackline for different school sizes was estimated. Using the 2006/07 BT-NSP data, for which there were confirmed school sizes, detection on the trackline for solitary animals was 0.46 (cv=27%) fitting school size as a continuous variable model and 0.29 (cv=38%) fitting school size as a factor variable. As expected, detection on the trackline increased with school size with single animals having a substantially lower probability of detection than groups of two or more animals. As noted above, in order to maximise the sighting rate (and hence the number of duplicate detections) for this experiment, all the trials of BT-NSP mode in 2006/07 were carried out near the ice edge where school sizes would be expected to be larger than average.

In an MRDS analysis, the type of model is an important consideration and deciding between the full and independence model is not straightforward unless there is clear evidence that animals are moving in response to the survey vessel. For stationary animals the point independence model is preferable to the full independence model because the rigorous assumptions of the full independence model maybe unlikely to hold; however, the point independence model is not tenable if there is responsive movement. Although a weak diagnostic tool, Figure 2 does not suggest much, if any, responsive movement. The differences in the shape of the BT-NSP detection function for the primary observer (indicated by the histogram of perpendicular distances – left hand column in Figure 5) and the fitted MR model (right hand column) is typical of a) increasing unmodelled heterogeneity with increasing distance and /or b) attractive movement between the tracker and the primary. The unmodelled heterogeneity may occur because the primary and trackers were searching the same region. This lack of separation of search regions may be due to several factors: all observers were using binoculars; good weather was experienced, particularly in 2005/06; and although the trackers were using BE, the tracker platform was considerably lower than the primary platform. The effects of unmodelled heterogeneity can be alleviated by separation of the search regions of the tracker and primary observers, however, the results of the BT-NSP trials suggest that there was considerable overlap of search regions and that using BE binoculars on the upper bridge did not demonstrate a substantial improvement in detection of minke whales compared with standard SOWER methodologies. In view of the lack of evidence of responsive movement and the overlap in primary and tracker search regions, the estimates from the point independence model than the full independence estimates are preferable. The BT-option 2 configuration encourages a clearer separation of search regions and the similarity of the DS plot and the MR plot for this data indicates that the effects of any unmodelled heterogeneity was reduced.

BT-NSP mode has provided an estimate of probability of detection on the trackline for the barrel. However, this analysis does not give an indication of the probability of detection on the trackline for the other platforms which are also used during the standard SOWER search protocols. For previous conventional DS estimates of minke whale abundance, the probability of detection on the trackline for all platforms combined was assumed to be one (Branch and Butterworth, 2001). An analysis of duplicate sightings recorded on previous SOWER cruises may provide an insight into the probabilities of detection on the trackline for other platforms.

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Table 1 Platform configuration for the different search modes; a) standard SOWER modes and b) BT modes. Platform height is in metres above sea level (masl). Although there are five observers on the upper bridge for all modes, the level of search effort is variable as data recording, tracking and assessment of duplicate status is also undertaken from that platform.

a) Standard SOWER modes

Trial	Platform	Binocular type	Platform height (masl)	No. of observers on platform
Closing/NSPmode	Barrel	7x50	19.0	2
	Upper bridge	7x50	10.5	5
IO mode	Barrel	7x50	19.0	2
	IOP	7x50	14	1
	Upper bridge	7x50	10.5	5

b) BT mode

Trial	Platform	BT configuration	Binocular type	Platform height (masl)	No. of observers on platform
BT-IO	Barrel	Primary	7x50	19.0	2
	IOP	Primary	7x50	14	1
	Upper bridge	Tracker	x25 Big eyes	10.5	1
	Upper bridge	Tracker	7x50	10.5	5
BT-NSP	Barrel	Primary	7x50	19.0	2
	Upper bridge	Tracker	x25 Big eyes	10.5	1
	Upper bridge	Tracking assistance	7x50	10.5	5
BT-option 2	Barrel	Tracker	7x50	19.0	2
	IOP	Primary	Naked eye	14.0	2

Table 2 Percentage of sightings by platform recorded during full search modes from SOWER surveys 1985/86 – 2004/05.

	Closing mode		IO mode		NSP mode		All search modes	
Platform	All species	Minke	All species	Minke	All species	Minke	All species	Minke
Barrel	49	48	45	44	56	56	47	47
IO	-	-	28	27	-	-	17	16
Upper bridge	46	46	25	27	25	24	32	32
Other	5	6	2	2	19	20	4	5

Table 3 Bias correction factors for each platform. A dash indicates no correction was necessary.

Survey	Platform	Number of trials	Angle bias factor	Distance bias factor
2005/06	Barrel	42	-	1.047
	BE	12	-	1.090
2006/07	Barrel	36	0.944	-
	BE	12	-	1.137
2007/08	Barrel	36	0.934	1.056
	IOP (7x50 bins.)	36	-	1.045
	IOP (naked eye)	30	1.066	1.084

Table 4 Search effort and numbers of minke whale schools sighted (by both tracker and primary observers including duplicates).

Survey	Search mode	Effort (nm)	Numbers of schools			
			Minke	Undetermined minke	Like minke	Total
2005/06	BT-IO	127.4	22	8	-	30
	BT-NSP	1385.3	258	10	15	283
2006/07	BT-NSP	1 195.9	226	36	31	293
	BT-option 2	275.4	118	21	23	162
2007/08	BT-option 2	564.2	11	1	5	17

Table 5 Number of minke schools sighted by each platform and the number of duplicates. The duplicate columns are denoted by Tracker:Primary.

Survey	Search mode	Platform			Number of duplicates		
		Barrel	IOP	BE	BE:Barrel	BE:IOP	Barrel:IOP
2005/06	BT-IO	13	11	4	2	2	
	BT-NSP	242		41	21		
2006/07	BT-NSP	228		65	31		
	BT-option 2	101	61				27
2007/08	BT-option 2	10	5				2

Table 6 Numbers of minke whale sightings seen by each platform and school size. The numbers in parentheses in a) are the numbers of schools with confirmed school sizes.

a) BT-NSP

School size	2005/06			2006/07		
	Tracker	Primary	Duplicates	Tracker	Primary	Duplicates
	BE	Barrel		BE	Barrel	
1	17	98	6	15 (10)	80	3
2	8	57	3	15 (14)	56	6
3	8	42	6	8 (8)	34	4
4	3	12	3	8 (6)	22	6
5	3	12	2	9 (7)	14	4
6-9	1	14	1	6 (6)	11	5
≥10	1	7		4 (2)	11	3
All	41	242	21	65 (55)	228	31

b) BT-option 2

School size	2006/07			2007/08		
	Tracker	Primary	Duplicates	Tracker	Primary	Duplicates
	Barrel	IOP		Barrel	IOP	
1	36	19	2	2	3	
2	22	14	8	2		
3	19	14	9	1		
4	2	3		2	2	2
5	4	3	2			
6-9	5	3	2	2		
≥10	13	5	4	1		
All	101	61	27	10	5	2

Table 7 Summary of point independence models in a) and full independence models in b). The parameter $\hat{p}(0)$ is the estimate of the average probability of detection on the trackline for the primary observer. 'Average *p*' refers to the average probability of detection averaged over all explanatory variables. The variables are perpendicular distance (D), school size (S) and Beaufort sea state (B); the subscripts indicate the variable has been included as a factor variable and indicate the number of factor levels. Percentage coefficients of variation are given in parentheses.

a) Point independence models

Survey	Search mode	Primary	Tracker	DS model	MR model	$\hat{p}(0)$	Average *p*
2005/06	BT-NSP	Barrel	BE	$D + S_4 + B_3$	$D + S_4 + B_3$	0.688 (22.7)	0.166 (24.2)
2006/07	BT-NSP	Barrel	BE	D + S	D + S	0.509 (21.4)	0.172 (22.9)
	BT-option 2	IOP	Barrel	D	$D + S_4$	0.306 (49.3)	0.028 (52.1)

b) Full independence models

Survey	Search mode	Primary	Tracker	DS model	MR model	$\hat{p}(0)$	Average *p*
2005/06	BT-NSP	Barrel	BE	-	$D + S_4 + B_3$	0.660 (30.0)	0.222 (29.7)
2006/07	BT-NSP	Barrel	BE	-	$D + S_6$	0.419 (41.1)	0.240 (40.9)
	BT-option 2	IOP	Barrel	-	$D + S_4$	0.245 (59.4)	0.084 (58.8)

Table 8 Probability of detection on the trackline by school size fitted to 2006/07 BT-NSP BE only data and BT-option 2 data. In the full independence model fitted to BT-NSP BE data and the model fitted to the BT-option 2 data school size has been fitted as a factor variable.

School size	BT-NSP BE only		BT-option 2
	Point independence	Full independence	
1	0.460 (27.8)	0.284 (40.8)	0.133 (65.8)
2	0.506 (25.0)	0.590 (21.8)	0.685 (14.5)
3	0.552 (23.4)	0.646 (28.3)	0.685 (17.3)
4	0.597 (22.2)	0.914 (7.6)	0.880 (8.6)
5	0.641 (21.0)	0.654 (29.9)	
6	0.682 (19.6)	0.890 (13.1)	
7	0.721 (18.1)		
8	0.757 (16.6)		
9	0.789 (15.1)		
10	0.818 (13.7)		
20	0.966 (5.13)		

Fig. 1. Plot of search effort in BT mode during 2005/06, 2006/07 and 2007/08. During 2005/06 and 2006/07 research was conducted in the vicinity of the ice-edge which changed substantially during the duration of the cruises;an approximate position of the ice-edge is indicated by the tracklines. The dashed grey line at the bottom of the plots indicates the coast of Antarctica.

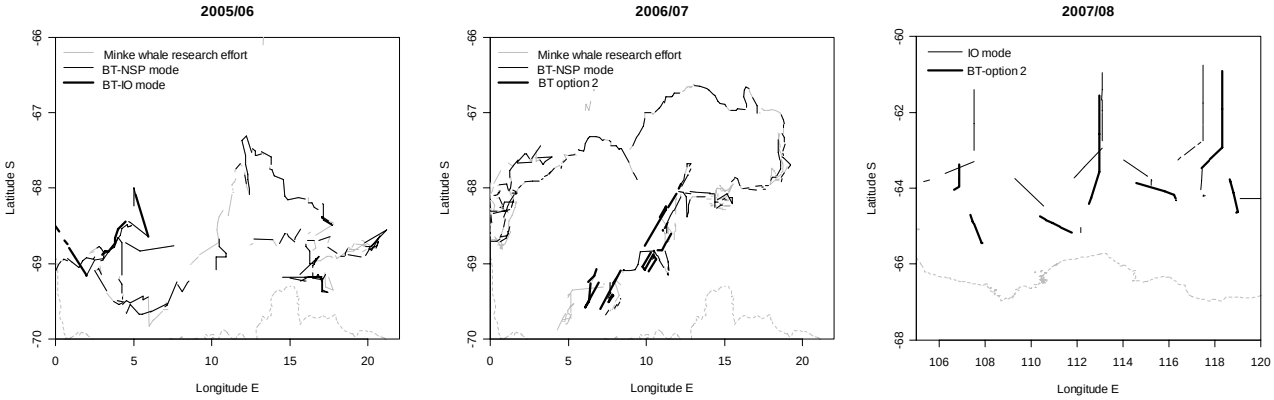


Fig. 2. Perpendicular distances of duplicates at the time they were detected initially by the tracker (*y*-axis) and then by the primary (*x*-axis). The dotted diagonal line corresponds to no movement. Points below the line correspond to movement away from the transect line, while those above correspond to movement towards it.

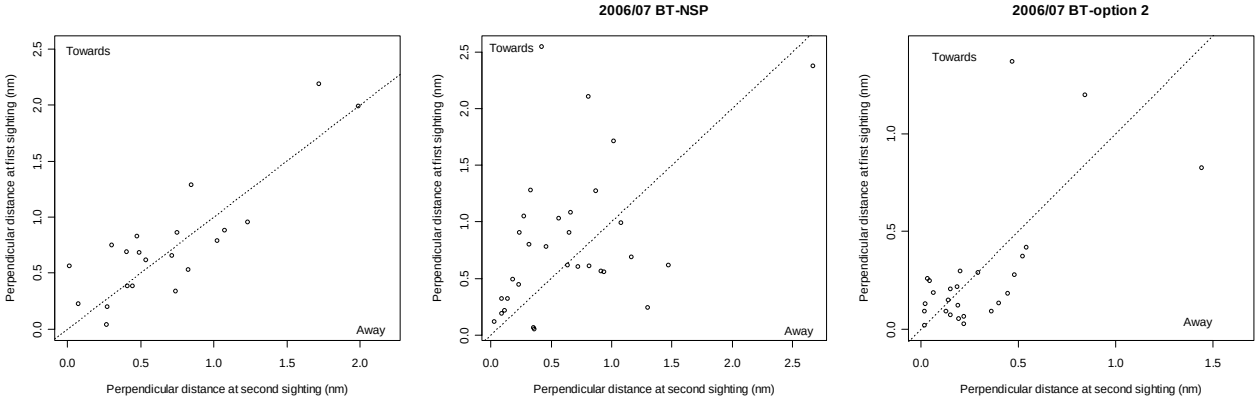
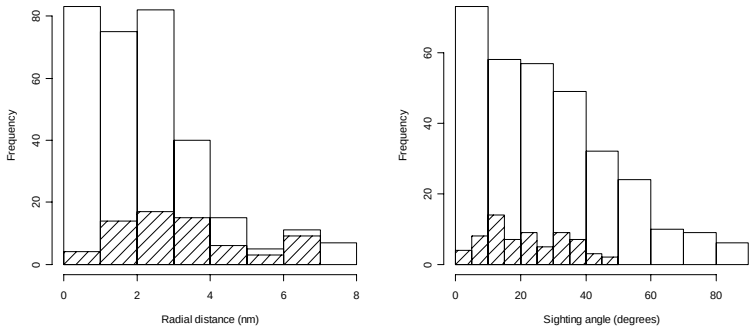
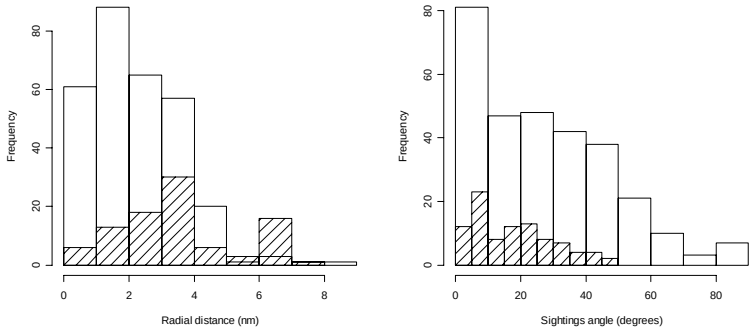


Fig. 3. Distributions of radial distances (left column of plots) and sighting angles (right column) for all sightings from all the platforms used in BT modes. In a) and b) the shaded regions are tracker (BE) sightings and unshaded are primary (barrel) sightings. In c) and d) the shaded regions are the primary (IOP) sightings and the unshaded regions are the tracker (barrel) sightings.

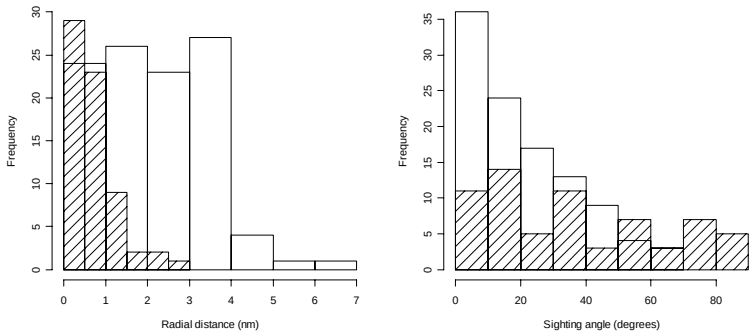
a) 2005/06 BT-NSP



b) 2006/07 BT-NSP



c) 2006/07 BT-option 2



d) 2007/08 BT-option 2

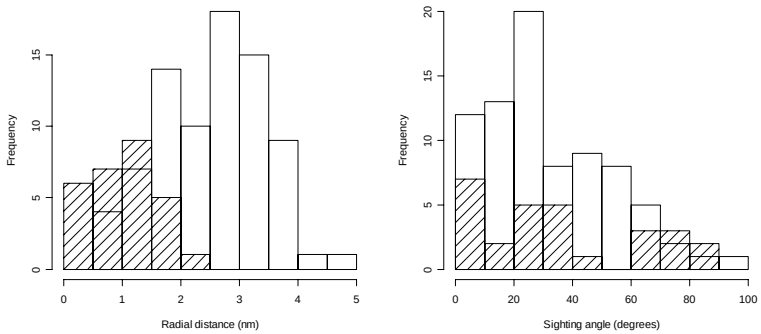
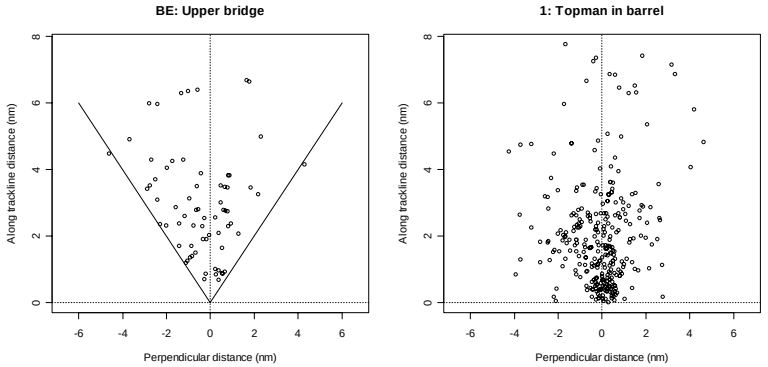
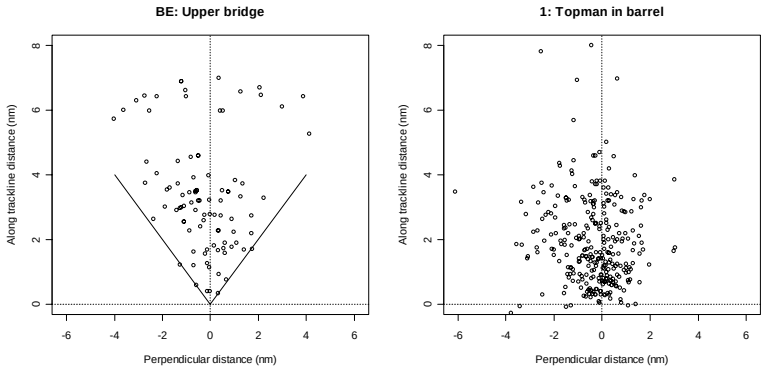


Fig. 4. Locations of detected sightings (all species) by platform. Lefthand column are trackers and the righthand column are primary observers. The lines on the tracker plots indicate 45° either side the trackline for BT-NSP model and 60° for BT-option 2.

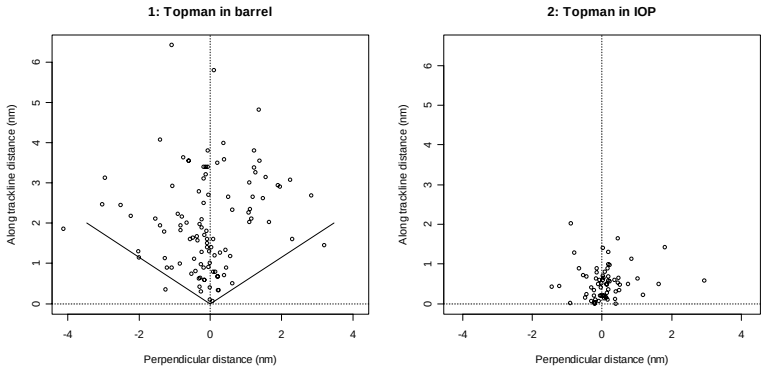
a) 2005/06 BT-NSP



b) 2006/07 BT-NSP



c) 2006/07 BT-option 2



d) 2007/08 BT-option 2

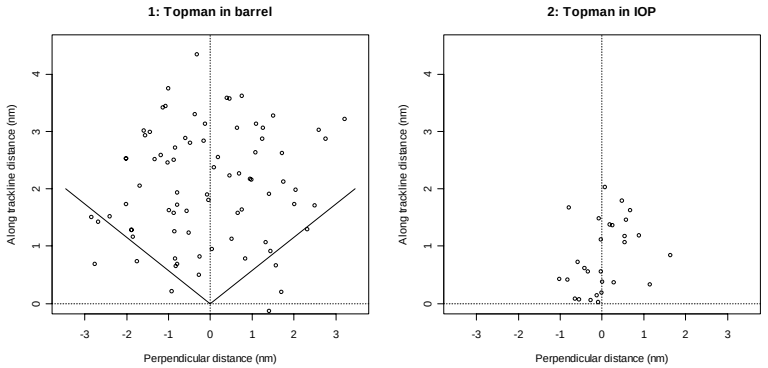
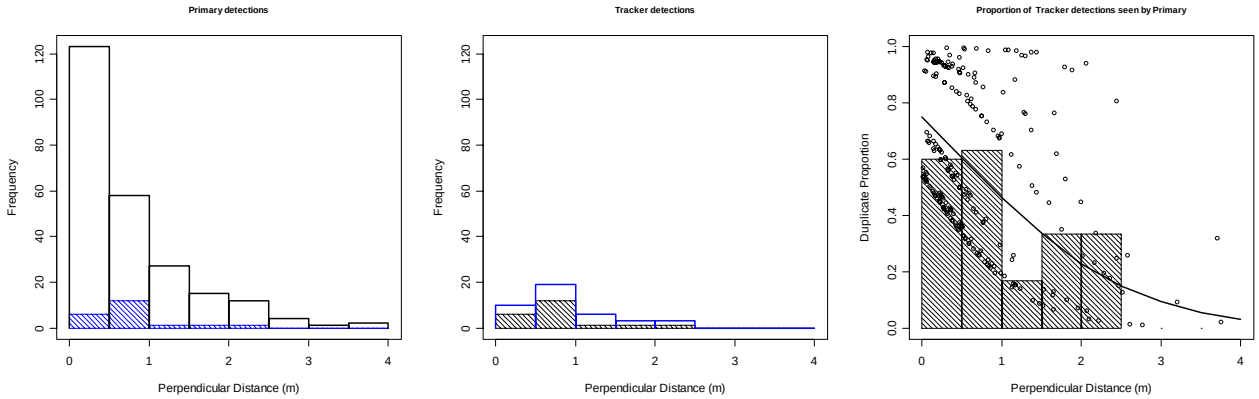


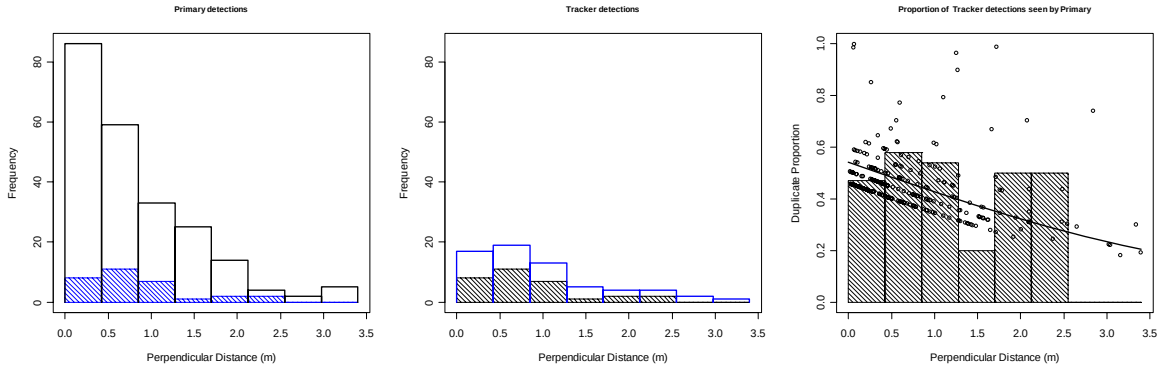
Fig. 5. Distribution of the perpendicular distances for the a) primary and b) tracker observers where the shaded regions indicate the number of the duplicates. Plot c) shows the proportion of duplicates to tracker sightings and the fitted MR model. The points are the estimated probability of detection for each observation (given its perpendicular distance and other explanatory variables). Distances are in nautical miles and have not been truncated.

a) b) c)

2005/06 BT-NSP



2006/07 BT-NSP



2006/07 BT-option 2

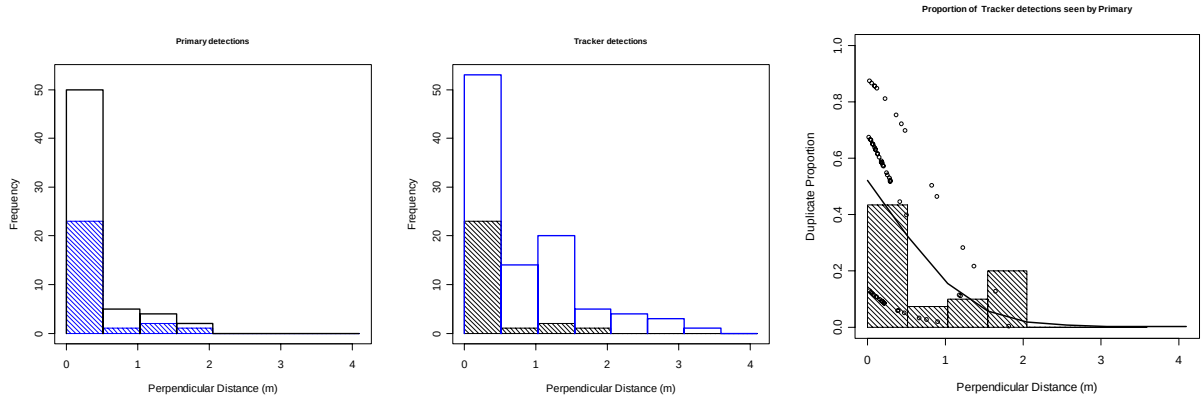


Fig. 6. Estimated probability of detection on the trackline for different school sizes estimated from the MR model fitted to the 2006/07 data. The lines are the 95% 'percentile' confidence limits. On the basis of AIC, school size was fitted as a factor in the BT-NSP full independence model (factor levels relate to school sizes of 1, 2, 3, 4, 5 and ≥6 animals) and with the BT-option 2 data (levels 1, 2, 3 and ≥4 animals).

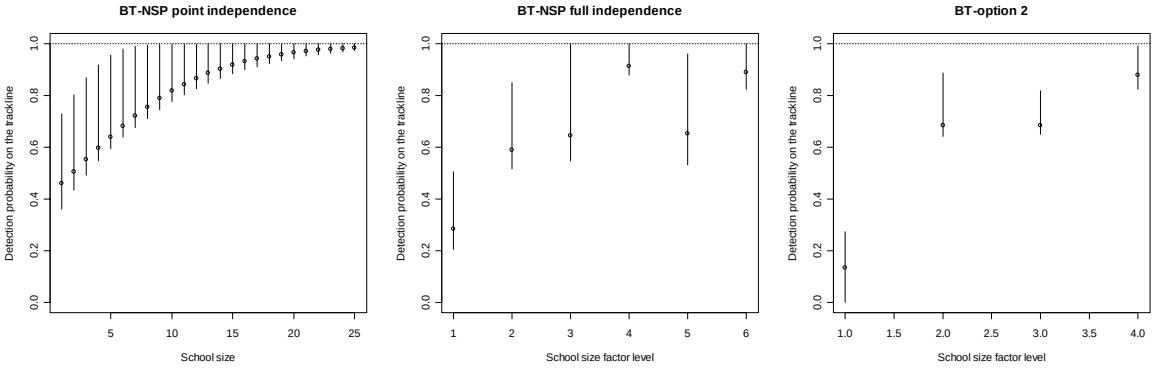
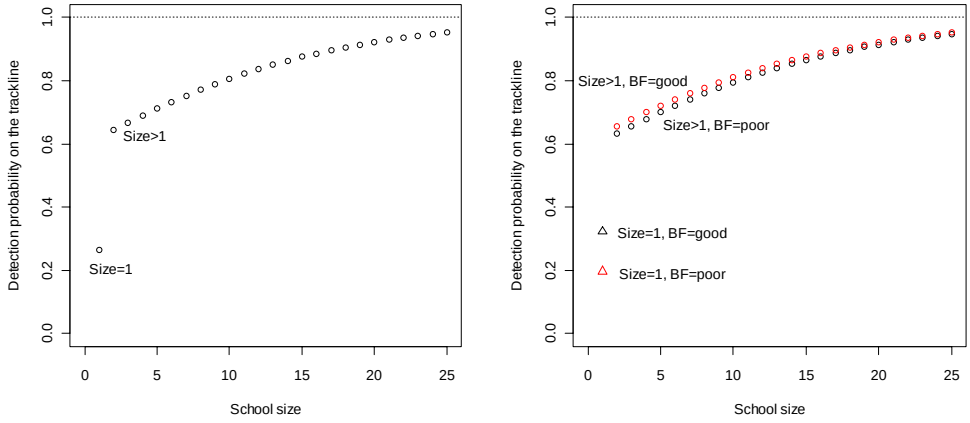


Fig. 7. Estimated probability of detection on the trackline for different school sizes estimated from the MR model fitted to the 2006/07 data including additional variables; a) a variable to indicate schools of size one or more, and b) as a) plus Beaufort (2 levels) and an interaction of these two variables.

a) b)