Correction factors account for the availability of bowhead whales exposed to seismic operations in the Beaufort Sea

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ABSTRACT

The accuracy of estimates of cetacean density from line-transect survey data depends in large part on how visible the target species is to the observer. Behavioural data (i.e. surface and dive times) from government- and industry-funded aerial observation programmes (1980–2000) were used to calculate availability correction factors needed to estimate the number of bowhead whales (*Balaena mysticetus*) from aerial survey sighting data. Correction factors were calculated for bowhead whales exposed and not exposed to seismic operations. Travelling non-calf whales were found to be less likely to be available for detection than other whales, and their availability further declined in the presence of seismic operations. Non-calves were also less available to observers during autumn when exposed to seismic operations than when not exposed, regardless of activity (travelling or otherwise)**.** Such differences in availability appear to reflect behavioural responses to the sound of seismic operations that alters the surfacing and diving patterns of bowhead whales. Localised abundance estimated from aerial surveys may range from 3% to as much as 63% higher in areas ensonified by seismic operations if correction factors are applied to account for differences in availability associated with the presence of seismic operations, compared to abundance estimates derived from assessments that only account for changes in availability of undisturbed whales. These results provide the first empirical estimates of availability for bowhead whales exposed to seismic operations and highlight the implications of not correcting for disturbance-related availability in density assessments in the vicinity of seismic operations.

KEYWORDS: *g*(0); SURVEY-AERIAL; NOISE; BEAUFORT SEA; BOWHEAD WHALE; LINE-TRANSECT; BEHAVIOUR; DIVING; MONITORING

INTRODUCTION

Aerial surveys are a common means to assess the abundance of animals that range over wide areas (Edwards *et al.*, 2007; Evans *et al.*, 2003; Forcada *et al.*, 2004; Hain *et al.*, 1999; Huber *et al.*, 2001; Laake *et al.*, 1997; Pollock *et al.*, 2006; Richard *et al.*, 2010; Southwell *et al.*, 2007). Such surveys typically use systematic line-transect methods and consist of one or more observers recording the numbers, locations and distances from the transect line of detected animals. These data are then analysed using methods such as distance sampling (Thomas *et al.*, 2010) to estimate the density of individuals that were present within the surveyed area. However, the accuracy of these estimates depends on the reliability with which the animals can be detected (Caughley, 1974; Marsh and Sinclair, 1989; Steinhorst and Samuel, 1989).

Distance sampling methodology incorporates a detection function $g(x)$ for modelling the effect of the perpendicular distance (x) from the transect line on the probability of detection. The quantity $g(0)$ is central to the concept of distance sampling (Buckland *et al.*, 2001), and denotes the probability of detecting an object given that it is on or near the transect line. Conventional line-transect methodology assumes that all animals on the transect line are detected (i.e. $g(0) = 1$; Buckland *et al.*, 2001). Hence, a source of negative bias in density estimates can occur when animals along the transect line either cannot be seen or are missed by observers (i.e. when $g(0)<1$).

The probability of failing to detect an animal is composed of two components, perception bias (animals that are potentially visible to observers but not seen) and availability bias (animals that are not available to observers because they are submerged or concealed) (Laake and Borchers, 2004; Marsh and Sinclair, 1989; Samuel and Pollock, 1981). These probabilities may be functions of animal behaviour, survey platform specifications and environmental factors (e.g. sea state and ice cover) (Caughley, 1974). It is therefore necessary to estimate and correct for any biases associated with perception and availability to obtain unbiased density estimates (e.g. Heide-Jørgensen *et al.*, 2010; Marsh and Sinclair, 1989).

Differences in availability make it particularly difficult to obtain unbiased estimates of cetacean abundance from aerial survey observations. Individuals or groups of cetaceans are generally considered available when they are at or near the surface of the water, and considered unavailable to be seen when submerged below the surface (Laake and Borchers, 2004). Availability for a species of cetacean may be estimated as a function of the proportion of time that individuals would be expected to spend at the surface, and the duration of time that the animal, even if submerged, would be within the range of detectability of the observer (described as the time-in-view). The expected proportion of time at the surface can be calculated from surface-respiration-dive (SRD) behaviour data (Hain *et al.*, 1999). The time that an animal may be in view can in turn be determined by survey speed, altitude and the field of view (Fig. 1) from the survey platform (Caughley, 1974; Forcada *et al.*, 2004; Hain *et al.*, 1999; Laake and Borchers, 2004). Consideration of these variables allows correction factors for

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availability to be estimated and incorporated into density estimates.

In the Beaufort Sea, aerial surveys are commonly used to study the distribution of the Bering-Chukchi-Beaufort Seas' population of the bowhead whale (*Balaena mysticetus*). Line-transect sightings data from industry-sponsored aerial surveys have also been used to monitor for effects of offshore industrial activities and estimate localised densities. These density estimates have been used to provide management with estimates of the number of animals exposed to different received levels of seismic sound (Brandon *et al.*, 2011). In the Beaufort Sea, offshore industrial activities occur primarily during the late summer and autumn when the waters are often ice-free and most easily accessible. Hence, industry-sponsored aerial surveys have also occurred during that time.

The westward migration of this bowhead population also occurs during the late summer and autumn (Moore and Reeves, 1993). The migration occurs in pulses (Blackwell *et al.*, 2007), segregated both temporally and spatially by age class, and bowhead distribution is influenced by sea-ice conditions and water depth (Koski and Miller, 2009; Ljungblad *et al.*, 1986; Moore *et al.*, 2000; Treacy *et al.*, 2006). While the predominant activity of bowhead whales at that time of year is travel, they sometimes pause to feed along the migration corridor at places and times where prey is abundant (Koski *et al.*, 2009). Activity state, age class, ice conditions and water depth influence the surface-respiration-dive behaviour of bowhead whales (Dorsey *et al.*, 1989; Richardson *et al.*, 1995; Robertson *et al.*, 2013; Würsig *et al.*, 1984), and potentially the proportion of time that they spend at the surface.

The durations of surfacings and dives of bowhead whales are also influenced by industry operations such as seismic exploration (Ljungblad *et al.*, 1988; Richardson *et al.*, 1986; Robertson *et al.*, 2013). The availability for bowhead whales was first assessed by Davis *et al.* (1982), who recognised the need to account for bowhead whales missed due to variations in their surface and dive behaviour. Davis *et al.* (1982) calculated the correction factors for availability following the method derived by McLaren (1961). More recently, Thomas *et al.* (2002) expanded the earlier work and calculated availability correction factors for presumably undisturbed bowhead whales engaged in different activities. Availability correction factors have not been previously published for bowhead whales or other cetacean species exposed to seismic or other industry operations.

Disturbance and other factors are known to influence surface-respiration-dive behaviour, but it is not known whether they also affect availability and the density estimates of bowhead whales calculated from line-transect surveys. While changes in the surfacing and diving variables noted above would be expected, they do not necessarily correspond with changes in availability. For example, the availability of whales would not change appreciably if they reduced (or increased) both their surfacing and dive times by ~25%. The objective of this study was therefore to assess whether the availability of bowhead whales to aerial observers differs in the presence and absence of seismic operations in the Beaufort Sea. Availability correction factors for bowhead whales in different reproductive states that were engaged in different activities during summer and autumn while in the presence and absence of seismic operations were estimated. The extent to which the presence of seismic operations could result in over- or under-estimates of the local abundance of whales, if this potential source of bias were not accounted for, was also assessed.

METHODS

Data sources and collection

Bowhead behaviour data were obtained from five studies conducted from 1980 to 2000 in the southern Beaufort Sea during summer and autumn. Summaries of these studies are provided by Koski and Johnson (1987), Richardson *et al.* (1986) and Richardson and Thomson (2002). All behavioural observations were made using the same standardised procedures as Würsig *et al.* (1985) and Richardson *et al.* (1985). In brief, the data were collected from fixed-wing aerial observation platforms in a manner that ensured whales were not appreciably disturbed by the observation aircraft (Patenaude *et al.*, 2002; Richardson *et al.*, 1985; 1987; Richardson and Thomson, 2002; Würsig *et al.*, 1985). The observations included whales that had not been recently exposed to seismic operations or other types of human activity (presumably undisturbed behaviour), as well as whales that were exposed to industrial or experimental sources of seismic sounds (potentially disturbed behaviour) (Dorsey *et al.*, 1989; Richardson *et al.*, 1985; 1987; Richardson and Thomson, 2002; Würsig *et al.*, 1985). The data included surface and dive durations. A dive, as recognised here, is based on the definition of a sounding dive by Würsig *et al.* (1984); a sounding dive is when a whale was submerged below the surface and out of sight for ≥60 seconds in duration.

Mean surface and dive durations were calculated for disturbed and presumably undisturbed whales in different reproductive states (non-calf whales, including adult and subadult whales, and cows with a dependent calf), for non-calves engaged in different activities (travelling, socialising and feeding), and for non-calves during summer and autumn. Sample sizes for surface and dive data are summarised in Table 1. Note that all whales classified as undisturbed were presumed to be undisturbed because no seismic activities or other human or industrial activities were occurring or had recently occurred in the region (this was determined if no air-gun pulses, or other industry related sounds were detected on sonobuoys) and the observation aircraft was >457m altitude. Data on surface and dive duration are key components in the calculation of bowhead whale availability.

Assessing the field of view from a Twin Otter

The field of view for an observer in a de Havilland Twin Otter aircraft was determined during September and October 2012. Twin Otter aircraft are one of the main platforms used for government- and industry-sponsored surveys for bowhead whales and other marine mammals in the Beaufort Sea. Visibility is often reduced within a certain lateral distance of the transect line and also forward and aft for these aircraft (Thomas *et al.*, 2002); therefore, complete detection on or near the transect line cannot be assumed even if all whales present were at the surface and available to be seen.

Table 1

Categories for which bowhead whale availability [$a(x)$] correction factors were calculated and the corresponding sample sizes of surface and dive data available. Only dives ≥60s were included for analysis. Correction factors by season and by activity state were calculated for non-calf whales only. Non-calf whales included all whales without a dependent calf.

	Seismic		Undisturbed		Total	
Category	Surface	Dive	Surface	Dive	Surface	Dive
Reproductive status:						
Non-calf	504	106	1,070	333	1,574	439
Cow with dependent calf	29	18	80	67	109	85
Season*						
Summer (3–24 August)	281	71	414	84	695	155
Autumn (25 August–10 October)	223	35	656	249	879	284
Whale activity						
Travel	79	18	120	77	199	95
Feed-shallow (≤20m depth)	46	21	258	97	304	118
Feed-deep (>20m depth)	38	20	213	47	251	67
Social	326	44	369	66	695	110

*25 August delineates the average start of the B-C-B bowhead population's migration west through the central Beaufort Sea (Richardson and Thomson, 2002).

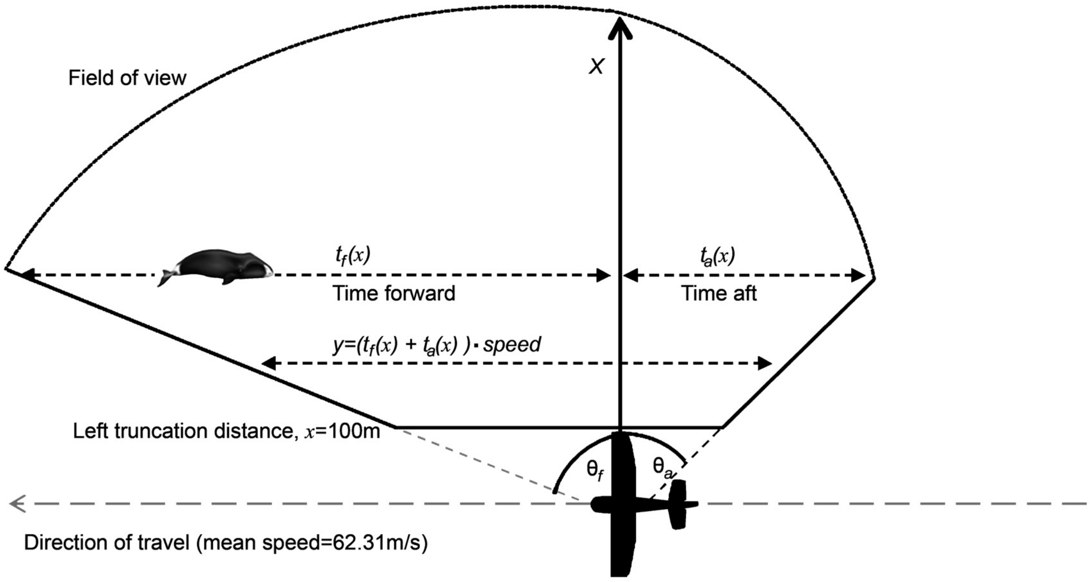

Fig. 1. A depiction of the field of view of an observer from a Twin Otter aircraft. The maximum visible range is denoted by X. Observers generally scan an area from $90 - \theta_f$ to $90 + \theta_a$, which gives a maximum angle of view. The field of view aft is smaller than might be expected because search effort is generally focused forward of the plane and perpendicular to it. The total time-in-view (time forward plus time aft) is a function of the perpendicular distance (x), survey speed and altitude, and was evaluated at $x = 100$m, the distance at which bowhead sighting data are generally left truncated. The lateral distance (y) is the swath of the sea surface that is within the observer's field of view.

For this reason, bowheads are only available for detection within a certain viewing area, an area referred to as the field of view.

The field of view is a function of the forward (θ_f) and aft (θ_a) angles-of-view, and a perpendicular distance representing the maximum visible range (X) from the transect line (Forcada *et al.*, 2004) (see Fig. 1). The survey platform, altitude and the scanning behaviour of the observer can affect the parameters of the field of view.

The field of view was estimated by combining the results of a dedicated experiment with a trigonometric modelling approach, similar to that presented by Forcada *et al.* (2004). The experiment to estimate the time-in-view for the Twin Otter aircraft consisted of flying the aeroplane along parallel tracks past a static object (in this case a small structure) at pre-selected discrete distances, increasing from 160m to 1,600m from the object. Each experiment was performed at a standard survey speed of 220km/h (averaging 62.3ms^{-1}) and an altitude of 305m above surface level. A single observer (FCR) was used to collect the data in this experiment. For each parallel track, the discrete distance was randomly selected and only known to the pilots, ensuring that the observer was not cued into a particular search pattern. The observer was asked to maintain their 'normal' search pattern (i.e. to avoid actively searching for the object) and record three time measures: (1) the time at which the object first came into view ahead of the aircraft (t_1); (2) the time when the object was perpendicular to the aircraft (t_2); and (3) the time when the object left the observer's view to the rear of the aircraft (t_3). Two time measures were calculated from these data: (1) time forward: $t_f = t_2 - t_1$ and (2) time aft: $t_a = t_3 - t_2$.

Linear models were fitted separately to the forward time-in-view and aft time-in-view data as a function of perpendicular distance (x), assuming normal sampling error on recorded times.

$$t_i = \alpha_i + \beta_i x \qquad (1)$$

where i denotes either forward or aft ($i = a$ or f) of the line perpendicular to the transect line, and α and β are the model coefficients, where β is the gradient of the line fit to the data. The forward and aft angles of view can then be derived from a trigonometric model using the model coefficient β_i:

$$\tan\theta_i = \beta_i \cdot speed \qquad (2)$$

The dimensions of the field of view allowed forward and aft view times to be evaluated at each perpendicular distance (x) from 0–2,000m, at 100m increments. A maximum perpendicular distance of 2,000m (X) was selected because bowhead sighting data are often truncated at a perpendicular distance of ~2,000m from the transect line (Fig. 1).

$$t_i(x) = \alpha_i + \frac{x \cdot \tan\theta_i}{speed} \qquad (3)$$

This allowed the lateral distances (y) at each perpendicular distance to be determined, where the lateral distance was the swath of sea surface within the observer's field of view in which a whale would have to be at the surface to be detected (Fig. 1). Based on previous aerial survey studies of bowhead whales in the Beaufort Sea (e.g. Funk *et al.*, 2011), sighting data collected from Twin Otter aircraft have been left-truncated at 100m; therefore, for the purposes of this study, we assumed that perfect detection (conditional on the animal being at the surface) should occur at 100m rather than on the transect line itself. Hence we evaluated t at a perpendicular distance of 100m from the transect line. Similar assumptions have been made by Forcada *et al.* (2004) and Hain *et al.* (1999).

Correction factors for availability

Availability correction factors [$a(x)$] were calculated for bowhead whales in the presence and absence of seismic operations and for whales of different reproductive states and for non-calf whales during summer and autumn and while engaged in different activities. Calves were excluded from the analysis because they had different dive profiles and were in close association with an adult whale (the mother). Observers often detect calves after their attention has been drawn to the mother. Correction factors for availability were thus calculated for whales in the presence and absence of seismic operations to determine whether the presence of seismic operations affected the probability of a bowhead whale being available to be seen during an aerial survey.

Availability correction factors were calculated following the method outlined by Laake *et al.* (1997) to describe the availability of harbour porpoise (*Phocoena phocoena*) during an aerial survey study in the coastal waters of Washington State. Their model treats the animals' surfacing and diving behaviour as an alternating Poisson process of being available (time at the surface, s) or unavailable (the length of the dive, d) (Laake and Borchers, 2004). Laake *et al.* (1997) assumed the lengths of the intervals s and d were independent exponential random variables with μ the rate parameter of s and λ the rate parameter of d. Thus the expected values of s and d are $E(s) = 1/\mu$ and $E(d) = 1/\lambda$. Under this model, $E(s) + E(d)$ is the expected length of the surface-dive cycle. Therefore, availability at perpendicular distance x, defined as the probability that an animal at perpendicular distance x will be at the surface at some point while within the observer's field of view, is:

$$P(x) = \frac{\lambda}{\lambda + \mu} + \frac{\mu\left[1 - e^{\{-\lambda t(x)\}}\right]}{\lambda + \mu} \qquad (4)$$

Time $t(x)$ in Eqn. 4 is the amount of time the ocean at perpendicular distance x is in the observer's view; Eqn. 4 can be re-written as:

$$P(x) = \frac{E(s)}{E(s) + E(d)} + \frac{E(d)\left[1 - e^{\{-\lambda t(x)\}}\right]}{E(s) + E(d)} \qquad (5)$$

(Laake *et al.*, 1997). Substituting sample means for expected values and $t(x)$ yields the availability correction factors:

$$a(x) = \frac{\bar{s}}{\bar{s} + \bar{d}} + \frac{\bar{d}\left[1 - e^{\{-t(x)/\bar{d}\}}\right]}{\bar{s} + \bar{d}} \qquad (6)$$

where $t(x)$ is time-in-view (t) evaluated at 100m (estimated using Eqn. 3). Correction factors were calculated for the different categories (e.g. reproductive status, activity state, season and exposure to seismic operations) based on their SRD data (Table 2). The Laake *et al.* (1997) method for estimating the probability that a whale would be at the surface and available for detection is suitable for animals that are considered to be intermittently available (e.g. a marine mammal). Intermittent availability is defined as occurring when an animal is available for more than an instant and its availability can change when it is within the field of view (Laake and Borchers, 2004).

The effect of not applying the correct availability correction factor to bowhead whale sighting data collected in the presence of seismic operations was investigated. The percentage change for abundance estimates was calculated using two correction factors. These were based on SRD estimates from: (i) presumably undisturbed whales; and (ii) those when seismic operations were present:

$$\%change = \frac{N_s - N_{ns}}{N_{ns}} \cdot 100 \qquad (7)$$

where N_{ns} is the estimated abundance of whales obtained when applying the availability correction factor for presumably undisturbed whales and N_s is the abundance estimate for whales in the presence of seismic operations when the appropriate availability correction factor for disturbed whales is applied.

The same approach was used to illustrate how much correction factors themselves vary, when they incorporate a field of view that has been estimated under different assumptions. Correction factors derived with our estimated field of view, $a(x_l)$ were compared to correction factors derived with a field of view that assumed a constant 1km

Table 2

Availability [*a*(x)] correction factors for presumably undisturbed bowhead whales and those exposed to seismic operations, as calculated from Eqn. (6). Bowhead behaviour data were collected from the southern Beaufort Sea; mean surface ($\bar{s}$) and dive durations ($\bar{d}$) are recorded in seconds and time-in-view (t) (40.85s) is evaluated at a perpendicular distance of 100m. Only sounding dives (≥60s) were included in the dive category in accordance with Würsig *et al.* (1984). Variance estimates (V) were calculated based on the multivariate delta method (Eqns. 9–10). The percentage by which abundance would be underestimated if the incorrect correction factor were applied is also given.

Category	Seismic				Undisturbed				% Change in abundance estimates
	$\bar{s}$	$\bar{d}$	*a(x)*	*se*	$\bar{s}$	$\bar{d}$	*a(x)*	*se*	
Reproductive status									
Non-calf	61.1	528.7	0.170	0.16	74.2	504.7	0.196	0.16	15
Cow with dependent calf	96.4	740.5	0.163	0.13	121.7	656.8	0.207	0.12	27
Season									
Summer	56.4	371.0	0.222	0.18	66.6	394.2	0.229	0.19	3
Autumn	67.0	848.6	0.117	0.10	78.9	542.0	0.190	0.16	63
Whale activity									
Travel	53.0	645.9	0.132	0.14	92.3	705.3	0.165	0.12	25
Feed shallow	55.8	408.5	0.204	0.16	69.5	373.3	0.244	0.21	20
Feed deep	72.6	639.8	0.157	0.18	66.3	524.6	0.179	0.20	14
Social	62.3	507.1	0.178	0.12	73.8	326.2	0.281	0.13	57

swath along the transect line, $a(x_2)$. For a plane travelling at a standard survey speed of 220km/h (averaging 62.3ms^{-1}), a 1km swath will be in view for 16.1 seconds. The difference between correction factors derived from different field of view estimates was calculated as:

$$\%difference = \frac{a(x_1) - a(x_2)}{a(x_2)} \cdot 100 \qquad (8)$$

Variance calculations

Variances specific to each estimated correction factor $a(x)$ were estimated using the multivariate delta method. From the multivariate delta method the variance is:

$$V = \left[\nabla^T P(\boldsymbol{X})\right]|_{\boldsymbol{X}=\gamma} \sum \left[\nabla P(\boldsymbol{X})\right]|_{\boldsymbol{X}=\gamma} \qquad (9)$$

where [$\nabla P(\boldsymbol{X})$] is defined by Eqn. 10 [$\nabla^T P(\boldsymbol{X})$] and is its transpose. The rewritten version of $P(\boldsymbol{X})$ makes clear that it is a function of the random variables s, d and $t(x)$, which are independent by assumption – which is further simplified in Eqn. 10 by writing t in place of $t(x)$. Therefore $\boldsymbol{X}$ is a column vector with elements s, d and t; $\boldsymbol{\gamma}$ is a column vector with elements the estimated mean values $\bar{s}$, $\bar{d}$ and t; and $\sum$ is a three by three diagonal matrix with the variances $V(\bar{s})$, $V(\bar{d})$ and $V(t)$ on its diagonal. The notation $|_{X=\gamma}$ means that the corresponding vector of the partial derivatives of the re-written version of $P(\boldsymbol{X})$ with respect to s, d and t is to be evaluated at $\boldsymbol{X} = \boldsymbol{\gamma}$.;

RESULTS

The field of view for a Twin Otter

The experiment to determine the field of view for a Twin Otter was conducted opportunistically 18 times over a two-month period with the same observer (FCR) on each occasion. Line-transect surveys were conducted at a mean survey speed of 62.31ms^{-1}. Linear models fitted to the forward and aft time-in-view data provided the coefficients used to estimate the fore and aft angles (θ) that determined the boundaries of the area searched by the observer (Fig. 2). The coefficients estimated for the forward time-in-view data were 31.41 (SE = 7.17) for α and 0.02 (SE = 0.007) for β, while the coefficients for the aft time-in-view data were 6.37 (SE = 1.42) for α and 0.01 (SE = 0.001) for β. Hence the total time-in-view on the trackline was estimated to be 37.78s. This resulted in a search sector that spanned from 37.4° forward to 121.2° aft (where 0° is ahead of the plane and 90° is perpendicular to the transect line) for the Twin Otter survey aircraft used in this experiment (Fig. 1). Given the assumption that perfect detection occurs at a perpendicular distance of 100m from the transect line, the time that a whale could be within the field of view at an average survey speed of 62.31ms^{-1} and 305m survey altitude was 40.85s (95%CI = 32.89–48.82s). The corresponding distance parallel to the track line and in view to an observer given t at a perpendicular distance of 100m was 2.55km.

$$\left[\nabla P(\boldsymbol{X})\right]|_{\boldsymbol{X}=\gamma} \begin{bmatrix} -\frac{d\left(1-e^{\left(-t/d\right)}\right)}{(d+s)^2} - \frac{s}{(d+s)^2} + \frac{1}{d+s} \\ -\frac{d\left(1-e^{\left(-t/d\right)}\right)}{(d+s)^2} - \frac{s}{(d+s)^2} + \frac{1-e^{\left(-t/d\right)}}{d+s} - \frac{e^{\left(-t/d\right)}t}{d(d+s)} \\ \frac{e^{\left(-t/d\right)}}{d+s} \end{bmatrix} \qquad (10)$$

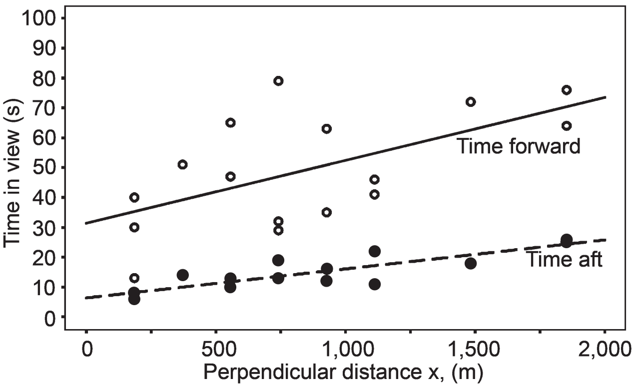

Fig. 2. Linear models fitted to the forward and aft time-in-view data collected during the 18 sampling occasions. The resulting *a* and *b* coefficients were incorporated into the trigonometric model used to estimate the field of view that observers scan while surveying (Eqn. 1–3).

The effect of exposure to seismic operations on availability of bowhead whales

The presence of seismic operations resulted in a lower probability of bowhead whales being available for visual detection within the observer's field of view (Table 2). For a presumably undisturbed non-calf whale, the overall probability of it being available for detection was $a(x) = 0.196$; however this dropped to $a(x) = 0.170$ in the presence of seismic operations. The probability of a cow with a dependent calf being at the surface and available for detection was $a(x) = 0.207$, and higher than that for the average non-calf whale in presumably undisturbed conditions. In the presence of seismic operations, however, the availability of whales with dependent calves declined to $a(x) = 0.163$ (Table 2). Both non-calf whales and cows accompanied by dependent calves displayed a lower probability of being available for visual detection in the presence of seismic operations. Not correcting for this difference in availability (i.e. failing to apply the appropriate correction factors for whales potentially disturbed by seismic operations) would have resulted in an underestimation of the estimated number of whales by 15% for non-calves and 27% for cows with dependent calves.

The presence of seismic operations had little effect on the availability of non-calves in the summer. In the autumn, however, the availability of non-calf bowhead whales decreased by almost one third in the presence of seismic operations (Table 2). Non-calves exposed to seismic operations were the least available for visual detection in the autumn. Abundance estimates of non-calf whales exposed to seismic operations in the autumn would be underestimated by 63% if the effects of seismic operation activity on whale behaviour were not accounted for.

There was a similar effect of seismic operations on non-calves that were travelling, socialising and feeding. The probability of being available for detection declined for all behaviours in the presence of seismic operations (Table 2). When whales were presumably not disturbed, travelling whales had the lowest probability of being available for detection ($a(x) = 0.165$). Their availability dropped further when seismic operations were present to $a(x) = 0.132$ (Table 2). Abundance estimates of travelling whales in the presence of seismic operations would be underestimated by 25% if appropriate correction factors were not applied. Undisturbed socialising whales exhibited the greatest probability of being available for detection, but their availability declined by 57% in the presence of seismic operations. Seismic operations also resulted in a lower probability of feeding whales being available for detection, although the effect was less than that for travelling or socialising whales (Table 2). Numbers of feeding whales exposed to seismic operations would be underestimated by 20% for whales feeding in shallow waters and 14% for whales feeding in deep waters if appropriate correction factors were not used (Table 2). Overall, estimates of abundance for bowhead whales may range from three, to as much as 63% higher in areas ensonified by seismic operations if correction factors were not applied to account for behavioural changes.

Correction factors derived with the time-in-view estimated for this study ($a(x_1)$, $t = 40.85$s) and a time-in-view that assumed the field of view was a constant 1km swath of water ($a(x_2)$, $t = 16.1$s) varied by 17%–34% (Table 3). These results highlight the effect of the field of view on availability correction factors. The results of the experiment to determine the field of view for a Twin Otter suggested that t increased as a linear function of perpendicular distance (Fig. 2). This implies that estimates of bowhead whale density derived

Table 3

A comparison of the availability [$a(x)$] correction factors for presumably undisturbed bowhead whales and those exposed to seismic operations derived from a time-in-view (t) of 16.1s for a lateral distance of 1km, and a t of 40.85s calculated using the methods proposed by this study, equating to a lateral distance of 2.55km.

	Seismic			Undisturbed		
	a(x)			*a(x)*		
Category	$t = 16.1$	$t = 40.9$	% Difference in *a(x)*	$t = 16.1$	$t = 40.9$	% Difference in *a(x)*
Reproductive status						
Non-calf	0.130	0.170	30	0.155	0.196	26
Cow with dependent calf	0.134	0.163	21	0.177	0.207	17
Season						
Summer	0.169	0.222	32	0.179	0.229	28
Autumn	0.091	0.117	29	0.153	0.190	25
Whale activity						
Travel	0.099	0.132	34	0.136	0.165	22
Feed shallow	0.154	0.204	32	0.192	0.244	27
Feed deep	0.124	0.157	27	0.139	0.179	29
Social	0.137	0.178	30	0.224	0.281	25

from aerial surveys should account for survey specific variables (such as survey platform, survey speed, observer search patterns and altitude) as well as whale behavioural changes.

DISCUSSION

This is the first study to investigate and quantify availability for bowhead whales exposed to seismic operations. The results indicate that the probability that a bowhead whale will be available for visual detection is lower when whales are exposed to seismic operations. Hence, if appropriate correction factors are not taken into account, the number of bowhead whales estimated to be in seismic survey areas exposed to various sound levels from seismic operations would be underestimated. Conversely, estimates of avoidance of seismic operations would be overestimated. The probability of detecting a bowhead whale within the field of view of an observer is lowest in the autumn when whales are migrating west through areas of the Beaufort Sea where there are (at some places and times) offshore industry activities, including seismic surveys. In general, at least during the autumn migration, the presence of seismic operations leads to a lower probability of bowhead whales being available for visual detection. A similar potential bias may exist for other whale species exposed to seismic operations.

Availability correction factors calculated in earlier studies were for bowhead whales that were presumed to be undisturbed (e.g. Davis *et al.*, 1982; Thomas *et al.*, 2002) and were specific to the aerial survey protocols of those individual studies. The field of view, and therefore the time-in-view (t) for observers to detect an animal at the surface, on or near the transect-line, is specific to the survey platform and is a function of platform specifications, survey speed, altitude and the individual observers (Caughley, 1974). Therefore, t may vary between surveys, especially if different observers, survey platforms, survey speeds, altitudes and strip widths or scanning patterns are used; availability correction factors derived for one survey may lead to inaccurate results if used in the analysis of data collected from a different platform under differing conditions (Marsh and Sinclair, 1989; Pollock and Kendall, 1987).

Earlier studies conducted in the Beaufort Sea estimated the time-in-view (t) to be between 18s (Davis *et al.*, 1982) and 21.6s (Thomas *et al.*, 2002). These estimates of time-in-view are shorter than the time-in-view at 100m from the trackline of 40.85s that we calculated for a Twin Otter aircraft (with bubble windows) flying at an altitude of 305m, at a standard survey speed of 220km/h. Likewise, the correction factors calculated with different field-of-view assumptions explored in these analyses differed by 17% to 34%. Despite these differences, as long as sightings data are limited to the field of view used to derive an availability correction factor, the application of that correction factor to those data is appropriate. On the other hand, if there is a difference between the field of view used to collect sightings data and that assumed to derive an availability correction factor, bias can be introduced into resulting estimates of densities and abundance. The experimental data used here to model t confirmed that the field of view was not constant across increasing perpendicular distances for a Twin Otter with bubble windows. It is thus important to consider survey specific data and observer search patterns when calculating t to obtain accurate density estimates of whale numbers within survey areas.

The proportion of time that a whale spends at the surface during a typical surface-respiration-dive (SRD) cycle and the time-in-view (t) of a location on the water are the key components needed to assess the availability of a whale for visual detection. Variations in SRD behaviour affect the overall proportion of time that whales spend at the surface, such that a whale that spends a higher proportion of its time submerged, and is therefore unavailable for detection, will decrease the probability of this whale being available for detection. Activity state, season, reproductive status and exposure to seismic operations all influence the availability of a whale for visual detection.

Subtle variations in SRD behaviour of bowhead whales exposed to seismic operations have been identified in early behavioural response studies (Koski and Johnson, 1987; Ljungblad *et al.*, 1988; Richardson *et al.*, 1985; 1986). During the autumn when whales are migrating west through the central Beaufort Sea and have been exposed to seismic operations there, travelling is the primary activity, interspersed with occasional feeding bouts (Koski *et al.*, 2009; Richardson and Thomson, 2002). It is during this time and for travelling whales that the more recent analysis of pooled behavioural data (from studies conducted during 1980 to 2000) found non-calf bowhead whales to be most responsive to seismic operations (Robertson *et al.*, 2013). Our correction factors based on the same behavioural data are consistent with this finding and suggest that non-calf bowhead whales are the least available for visual detection while travelling and in the autumn when exposed to seismic operations. Variation in the availability of a whale for visual detection may result in underestimates of the number of whales exposed to various levels of seismic operations in the Beaufort Sea, especially in autumn, and for travelling bowhead whales.

The surface and dive behaviour of bowhead whales varies with activity state. Differences in behaviours among activity states are also reflected in a whales' availability for visual detection. Thomas *et al.* (2002) determined that travelling whales had the lowest probability of detection while whales engaged in social activities had the highest probability of detection. Our study corroborates this finding for presumably undisturbed bowhead whales. However, the availability for detection declines by over a third when socialising whales are exposed to seismic operations, a level that is below that of whales feeding in shallow waters in the presence of seismic operations.

A large seasonal effect of seismic operations on the availability of bowhead whales was also determined. Most notably, seismic operations had little effect on whale availability during summer when feeding is the predominant activity (Würsig *et al.*, 1985). However, during autumn, seismic operations had a notable effect on the availability of whales when travelling becomes increasingly more common as the whales begin their westward migration. Previous assessments of availability (e.g. Davis *et al.*, 1982; Thomas *et al.*, 2002) focussed on presumably undisturbed bowhead whales, and therefore, are not applicable in analyses of sighting data collected in the presence of seismic and possibly other industrial operations.

During autumn, non-calves exposed to seismic operations have a low probability of being available for detection, followed by presumably undisturbed non-calves that are travelling. This is consistent with the finding that whales observed in the autumn or engaged in travel are more sensitive to seismic operations than are whales engaged in feeding (Koski and Miller, 2009; Robertson *et al.*, 2013). Undisturbed bowhead whales in the eastern and central Beaufort Sea spend the majority of the late summer and early autumn feeding, but also spend approximately one-third of their time travelling (Würsig *et al.*, 2002). During years of particularly low prey density, the time whales spend travelling increases as whales continue their westward migration rather than stopping to feed (Würsig *et al.*, 2002).

Bowhead whales react to seismic operations by subtly changing their SRD behaviour (Koski and Johnson, 1987; Ljungblad *et al.*, 1988; Richardson *et al.*, 1985; 1986; Robertson *et al.*, 2013), which affects the proportion of time that they spend at the surface. These changes are reflected in the probability of the whales being available for detection during an aerial survey. Aerial surveys are commonly part of environmental monitoring programmes for oil and gas exploration in the US Beaufort Sea (Funk *et al.*, 2011). These surveys monitor marine mammal presence and distribution relative to the industry's operations. Some surveys have applied alternate correction factors to account for bowhead whale activity (Thomas *et al.*, 2002). More recent surveys have begun to use availability correction factors that also account for the presence of active seismic operations (Brandon *et al.*, 2011). Nevertheless, results from earlier surveys that did not apply availability correction factors that account for seismic activity likely underestimated the numbers of whales potentially exposed to seismic operations and overestimated avoidance of seismic operations.

The presence or absence of industrial operations and the activity states of the whales seen during surveys will dictate which $a(x)$ estimate should be incorporated into the density analyses. For example, should a survey yield adequate sighting data where the majority of whales were observed feeding in an area with active seismic operations, then it is appropriate to select the correction factor for potentially disturbed feeding whales adjusted by the their value of $a(x)$. Alternatively, analyses of surveys without information on activity states would be stratified by season with the appropriate correction factor selected depending on whether or not seismic operations were present. Selection and use of the appropriate correction factors during analysis will lead to improved estimates of the number of whales exposed to different received levels of seismic sound, as required by regulators, for example, in the USA.

There are a number of limitations to the approach used in this paper to calculate the availability correction factors for bowhead whales exposed to seismic operations. The highly visible nature of the sighting object used in the time-in-view experiment meant that the field of view estimates likely represent the maximum potential detectability, and therefore the maximum time-in-view. The data collected during the time-in-view experiment influenced the choice to fit a linear model to the data. Ideally the pre-selected discrete perpendicular distances should have encompassed the transect line (0m), and the fact that it did not resulted in a lack of experimental observations on and very close to the transect line that may have influenced the overall fit of the model. Future experiments to estimate field of view should be designed so that pre-selected distances encompass the transect line, as well as utilise more realistic sighting objects, such as buoys on the sea surface. The latter would also allow, in principal, potential environmental effects (as discussed further below) to be incorporated in estimates of correction factors. The use of time recorded when the sighting object was perpendicular to the plane in both the calculation for time forward, $t_f = t_2 - t_1$ and time aft: $t_a = t_3 - t_2$ will have led to correlated errors. Future analysis of data collected under such a sampling design should consider the use of a joint-regression where the errors of t_1 and t_3 are independent but the errors of t_2 is the same for each calculation of t_f and t_a.

The time-in-view experiment also did not allow an investigation of the influence of environmental variables (e.g. sea state, sea ice coverage and glare) on the boundaries of the search area. During high sea states, for instance, observers may reduce their search area because it takes longer to decide whether a potential sighting is a marine mammal. Observer scanning behaviour and individual variation are also likely to influence the duration of detectability, and the time-in-view is based on measurements from a single observer. Future studies could likewise use a mixed-effects modelling framework to account for variation due to individual observer scanning behaviour, and also might produce better estimates of variance around the correction factors. Despite the limitations associated with this experiment, these results represent a first attempt to estimate a survey-specific time-in-view at the location where detection is assumed to be 1.0 for the Twin Otter aircraft commonly used for bowhead surveys in the Alaskan Beaufort Sea. These analyses have built on previous methods that have only estimated time-in-view based on aircraft speed (e.g. Davis *et al.*, 1982) or predetermined measures of the forward and aft angles of view (e.g. Forcada *et al.*, 2004).

The methods available to estimate the parameters associated with the field of view are an area of active research (Borchers *et al.*, 2013). A review of different methods may be warranted to understand their limitations and how differences between methods may influence overall estimates of availability. We acknowledge that there are limitations with the approach presented here resulting in a degree of uncertainty surrounding the final time-in-view estimates. However, this experimental approach has highlighted the need for further research into methods that can provide improved accuracy in field of view estimates, and ultimately detection patterns for marine mammals during aerial surveys.

Group size can influence how available whales are to being seen by observers. Groups of two or more whales, for example, tend to be more detectable to observers than single individuals. Surface-active groups of North Atlantic right whales (*Eubalaena glacialis*) have been found to have the highest availability with a mean of 93%, while the availability of individual right whales ranged from 40–60%

(Hain *et al.*, 1999). Bowhead whales engaged in surface skim feeding or socialising activities are often observed in groups of two or more whales (Würsig *et al.*, 1985; 1989). Such group activities by socialising bowhead whales and by whales feeding in shallow waters tend to increase disturbance of the surface waters, leading to higher probabilities of detection. The detection factors presented here are for individual whales.

Environmental, observer and whale related variables inevitably influence both the time-in-view as well as the overall availability of a bowhead whale for visual detection by an aerial observer. Although we were unable to account for the effects of many of these variables, these correction factors could be considered to be better than past values, but not optimal values for bowhead whales within each of the categories examined. Future measurements of the time-in-view in marine areas and subsequent estimates of bowhead whale availability should investigate and incorporate the effects of environmental, observer and whale related variables so that more accurate measures of detectability can be determined for a wider range of conditions.

Understanding how the behaviour, distribution and habitat use of bowhead whales are affected by industry operations is needed to evaluate the potential effects of oil and gas exploration and development activities on individual whales and their populations. These analyses have shown that seismic operations generally resulted in whales being less available for visual detection by aerial observers. Although these methods are specific to aerial observations of bowhead whales in the Beaufort Sea during summer and autumn, the same principles apply to aerial surveys and vessel-based surveys for other seasons, species and regions. Future studies investigating the effects of anthropogenic activities on cetacean distribution, local abundance and behaviour should calculate availability correction factors specific to the species of interest at the time and in the circumstances of exposure. This is necessary to avoid under- or over-estimating the number of whales exposed to potential sources of disturbance and to avoid over- or under-estimating the degree of avoidance around those activities. Such assessments require situation-specific data on surfacing and dive behaviour of the cetaceans, which can be obtained by visual methods (as shown here) or by tagging and telemetry methods. This information is needed to calculate appropriate correction factors for sighting data to better estimate the numbers of cetaceans that may have been exposed to disturbances (such as seismic operations). This information is needed in turn to determine how exposure to industrial activities influences the distribution of cetaceans and their choice of habitat.

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