

Vessel speed increases collision risk for the green turtle *Chelonia mydas*

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ABSTRACT: Vessel collisions contribute to the anthropogenic mortality of several threatened marine species including turtles, manatees, dugongs and whales, but scant data exist to inform the design of optimal mitigation measures. We conducted a field experiment to evaluate behavioural responses of green turtles *Chelonia mydas* to a research vessel approaching at slow, moderate or fast speed (4, 11 and 19 km h⁻¹, respectively). Data were recorded for 1890 encounters with turtles sighted within 10 m of the research vessel's track. The proportion of turtles that fled to avoid the vessel decreased significantly as vessel speed increased, and turtles that fled from moderate and fast approaches did so at significantly shorter distances from the vessel than turtles that fled from slow approaches. Our results imply that vessel operators cannot rely on turtles to actively avoid being struck by the vessel if it exceeds 4 km h⁻¹. As most vessels travel much faster than 4 km h⁻¹ in open waters, we infer that mandatory speed restrictions will be necessary to reduce the cumulative risk of vessel strike to green turtles in key habitats subject to frequent vessel traffic.

KEY WORDS: Green turtles · *Chelonia mydas* · Behaviour · Collision risk · Collision avoidance · Vessel speed · Go slow zones

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INTRODUCTION

Vessel collisions contribute to the mortality and morbidity of several marine taxa, notably turtles (Lutcavage et al. 1997, Environment Australia Marine Species Section 2003, Hazel & Gyuris 2006), sirenians (Ackerman et al. 1995, Greenland & Limpus 2005, Laist & Shaw 2006) and large cetaceans (Knowlton & Kraus 2001, Laist et al. 2001, Jensen & Silber 2003). Some affected species are of significant conservation concern in various jurisdictions, as a result of the cumulative effects of human-induced and natural mortality, habitat disturbance and low reproductive capacity, (e.g. US Fish and Wildlife Service 2001, Environment Australia Marine Species Section 2003, National Marine Fisheries Service 2005).

Vessel traffic has severely affected North Atlantic right whales *Eubalaena glacialis*, for which collisions have been identified as a major source of mortality (Knowlton & Kraus 2001), and Florida manatees *Trichechus manatus latirostris* where 25% of all docu-

mented deaths have been caused by collisions (Haubold et al. 2006). Stranding records for Queensland, Australia indicate that 7% of dead dugongs *Dugong dugon* had been struck by vessels (Greenland & Limpus 2006), as had 14% of dead sea turtles (Hazel & Gyuris 2006). These records are largely from populated areas of the state and comprise an unknown proportion of total mortality.

Management authorities have sought to mitigate vessel-related injuries to wildlife by identifying locations of particular importance for vulnerable species. Vessel operators are urged to increase vigilance within these areas, where recommended or obligatory routes and speed restrictions may apply. Other protective measures such as acoustic warning devices have been proposed (e.g. Gerstein 2002) but their utility in the wild remains uncertain. Proposed mandatory speed regulations for large vessels in some offshore areas have raised serious concerns about anticipated economic costs to shipping operators, who emphasize that speed regulation has not been con-

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firmed as an effective measure for reducing ship–whale collisions (World Shipping Council 2006). Furthermore, although speed restrictions in coastal waterways have been in place since the mid- or late 1990s at many locations in Florida and a few locations in Queensland, their intended role in reducing collisions between vessels and marine wildlife has not been clearly demonstrated.

There is, however, preliminary evidence from Merritt Island, Florida, that suggests speed restrictions can be effective in protecting manatees at some locations, provided the restrictions are refined to match site-specific conditions and provided compliance is assured by effective enforcement (Laist & Shaw 2006). These provisos appear difficult to achieve: variable levels of compliance with speed restrictions have been reported in many areas (e.g. Groom 2003, Gorzelany 2004, Hodgson 2004) and only scant data exist to inform the optimal design of speed restrictions.

Speed reduction strategies apparently derive from the expectation that slower speed should afford greater opportunity for both vessel operators and animals to identify imminent collision risks and take avoidance action. However, even the most vigilant vessel crews are unable to see submerged animals (except at close range in very clear water) and are unlikely to see surface animals in rough seas or under low light conditions. Therefore, in practical terms, this rationale would imply a high degree of reliance on animals to avoid vessels. Yet the capacity of various species of marine wildlife to detect and evade approaching vessels remains poorly understood, hampering the determination of wildlife-safe maximum speeds for vessels travelling in critical habitats.

Researchers have investigated behavioural responses to vessels by manatees (Nowacek et al. 2004) and dugongs (Hodgson 2004, Hodgson & Marsh 2007) but systematic field data are lacking for other species susceptible to collisions. Our study evaluated the ability of green turtles to avoid vessels and investigated behavioural characteristics of turtles that are potentially relevant to the reduction of collision risk.

MATERIALS AND METHODS

Study site and species. The study was conducted in shallow water (<5 m) along the north-eastern margin of Moreton Bay, Queensland, Australia during June to August 2004. The study site (Fig. 1) was selected because it provided

favourable foraging habitat for green turtles, and the combination of clear water and a light-coloured sandy substrate made it possible for an attentive observer on a moving boat to detect benthic animals with a high level of reliability.

Most turtles observed in the study area were positively identified as green turtles *Chelonia mydas*. A few loggerhead turtles *Caretta caretta* may have been present but undetected among submerged turtles sighted very briefly. Loggerheads are known to share habitat with green turtles in some parts of Moreton Bay (Limpus et al. 1994) but no loggerheads were actually identified during the entire study period. We assume that few loggerheads (if any) are included in our data.

Experimental trials. A 6 m aluminium boat powered by a 40 horsepower outboard motor was used to simulate transits of recreational boats travelling across the study site. One person drove this research vessel while a second person kept a safety lookout. A third person (the observer), positioned at the bow, maintained a continuous watch directly ahead and recorded all encounters with turtles.

The driver steered by compass bearing and visual reference to land features, and kept the vessel on a steady course that was independent of the presence of turtles. Animals below the sea surface were not visible from the driver's position at the rear of the vessel. Emergency stopping procedures were practised in advance to ensure they could be employed immediately if the observer or lookout person signalled danger. These measures proved effective; no collisions occurred. To avoid confounding effects, transits were temporarily suspended when other vessels approached.

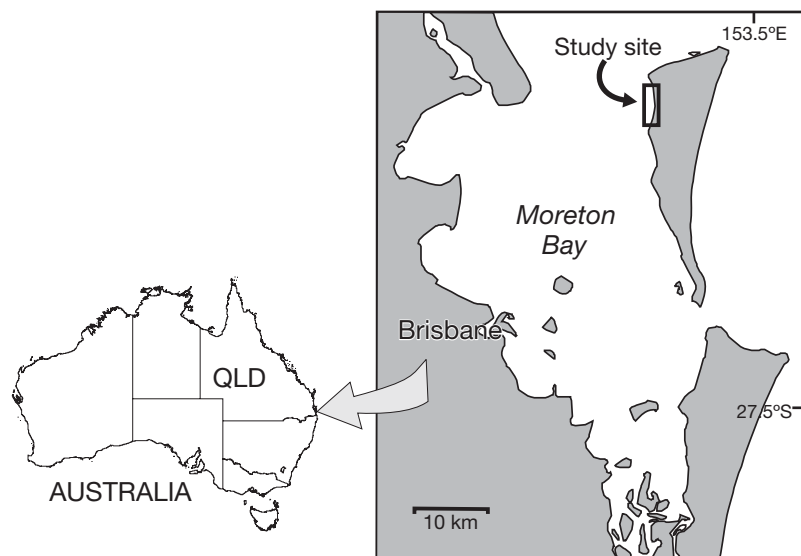


Fig. 1. The study site comprised an area of clear shallow water (<5 m) on the north-eastern margin of Moreton Bay, Queensland (Qld), Australia

Transits were conducted alternately northbound and southbound over a distance of approximately 5 km, roughly parallel to the shoreline. Distance from the shoreline (200 to 450 m) was varied from one transit to the next in order to distribute spatial coverage evenly, and to minimise the chance of sequential encounters with individual turtles. Each transit continued at least 300 m beyond the last turtle sighted and was followed by an interval (≥ 20 min) at anchor with the engine off.

All transits were conducted in water depths of 2 to 4 m. These limits were determined during preliminary trials to ensure the research vessel could pass safely over a grazing or resting turtle and the observer could see the substrate clearly. Water clarity was consistently good during the study period with vertical Secchi depths of 12 to 13 m measured in deeper water immediately adjacent to the study site. Experimental trials were restricted to 3 h before and after solar noon on days with good atmospheric visibility (no precipitation, predominantly clear sky) and calm or light wind (≤ 15 km h⁻¹). In addition, the observer re-evaluated visibility conditions before each transit and only allowed the trial to proceed if confident of detecting all turtles within 20 m of the vessel. When that criterion was not met, work was suspended temporarily (e.g. in the case of passing cloud or glare) or abandoned for the day (e.g. in the case of rising wind).

Three experimental speeds were chosen to reflect the operation of vessels ≤ 20 m length in Moreton Bay. 'Slow' speed, 4 km h⁻¹ (2 knots) approximated a lower limit for maintaining steerage; 'moderate' speed, 11 km h⁻¹ (6 knots), represented prudent operation near visible obstacles; 'fast' speed, 19 km h⁻¹ (10 knots), represented the lower range of unrestricted travel in open water. Many vessels in Moreton Bay routinely exceed 19 km h⁻¹, but safety and feasibility precluded experiments at higher speeds. Our speed definitions were broadly generalised to cover the diverse types of recreational and commercial vessels using Moreton Bay, and derive from our unpublished data and long-term personal experience, as well as published work (Maitland et al. 2006).

The speed of the research vessel was held constant, for the duration of each transit, by reference to a global positioning system receiver (GPS model Garmin 12, Garmin International). Accuracy of the receiver's velocity presentation was confirmed in separate time–distance trials. One of the 3 experimental speeds was assigned for each transit in an alternating pattern, subject to ambient conditions. It was sometimes necessary to conduct a slow or moderate transit in place of a fast transit, due to a minor increase in wind and sea state. We accepted the resulting imbalance in total encounters for the 3 speed categories as a necessary compromise in a field experiment subject to weather and time constraints.

While our main goal was to determine whether vessel speed influences collision risk for turtles, we also wanted to test a hypothesis (prompted by prior field observations) that turtles may rely on vision, rather than sound, to detect approaching vessels. For this purpose, the alternating direction of transits served as a proxy for manipulating underwater visibility. As the study was conducted during the austral mid-winter, the sun maintained a northerly azimuth at relatively low elevation. Underwater objects were visible to a diver at a greater distance when looking south (sun behind) than when looking north (sun ahead). Thus turtles were expected to have greater opportunity for visually detecting a north-bound vessel (turtle looking south, sun behind) than a south-bound vessel (turtle looking north, sun ahead).

Data recording and analysis. During each transit the observer recorded all encounters with turtles sighted within 10 m of the vessel's track. The 10 m limit was adopted to standardise sighting conditions. Preliminary trials had established that benthic turtles were detected by the observer at ≥ 20 m but that those beyond 10 m very rarely fled from the vessel. Distances were determined by visual estimates and must be regarded as approximate, since calibration was not feasible. To promote consistency, all observations were made by the same observer (J. Hazel) and estimates were constantly referenced against the known dimensions of the research vessel. Shorthand notation was used to allow rapid data recording without compromising the continuity of observation.

For each encounter the observer recorded the turtle's vertical position (benthic, in the water column or at the sea surface) and estimated the lateral offset distance between the turtle and the vessel's track (1 in Fig. 2a). The outcome of the encounter was recorded as 'Flee' if the turtle abruptly commenced swimming before the bow of the vessel (or a perpendicular line projected from the bow) passed the turtle's initial position. If the turtle did not flee before the vessel passed, the outcome was recorded as 'No Response'.

Additional information was recorded for each 'Flee' observation, comprising the forward distance at the moment the turtle initiated its flight (2 in Fig. 2a) and the direction of the turtle's initial flight trajectory (Fig. 2b–d). Forward distance and lateral offset distance were subsequently used to calculate the flight initiation distance (FID), defined as the shortest distance between the turtle and the bow of the vessel at the moment the turtle responded (3 in Fig. 2a).

At each encounter the turtle was classified as 'large' (estimated size range 85 to 110 cm curved carapace length) or 'small' (estimated size range 65 to 75 cm curved carapace length). Under the experimental con-

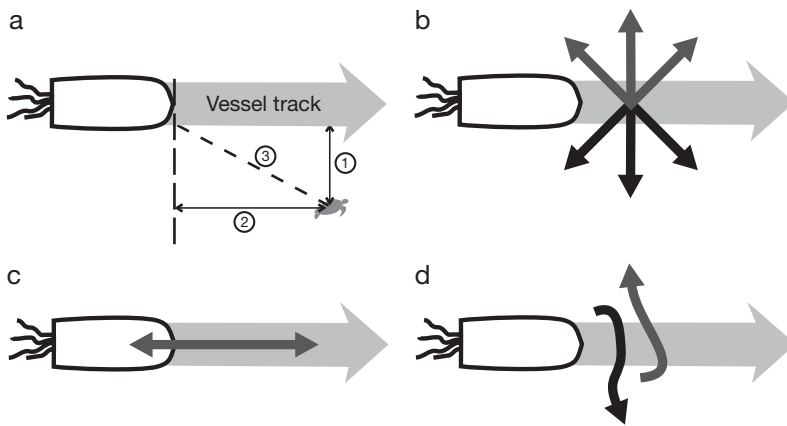


Fig. 2. *Chelonia mydas*. (a) For each vessel–turtle encounter the observer estimated the lateral offset (1) of the turtle. If the turtle fled, the forward distance at the moment of response was also recorded (2). These 2 distances together allowed calculation of the flight initiation distance (3). For each flee response the turtle's initial flight trajectory was classified as (b) safe (c) in-track or (d) cross-track

whether flight initiation distances were independent of speed categories we used the Mann-Whitney test, since data did not meet underlying requirements of parametric tests (Zar 1999). We report test results as significant at the 0.05 level.

RESULTS

The experiment comprised 1890 encounters with turtles. The overwhelming majority (1876, 99%) were large turtles (estimated curved carapace length 85 to 110 cm). In most encounters (1832, 97%) the turtle was foraging or resting on the substrate when sighted. These were dubbed 'benthic turtles'. Our results refer to observations of large benthic turtles (n = 1819) except where explicitly noted otherwise.

ditions, the 2 size categories could be differentiated readily by an observer familiar with the size range of the local green turtle population. It was deemed appropriate to analyse data separately by size category because small turtles typically display greater agility in their movements (noted during our related studies that involve hand-capture of study turtles) and therefore might evade vessels more readily than large turtles.

Some individuals were probably encountered several times over the duration of the study. As there was no way to identify individuals we did not use repeated measures analyses. We used the chi square test to determine whether the frequency of flee responses was independent of the experimental speed categories. To determine

Effect of vessel speed on frequency of flee responses

Turtles fled frequently in encounters with a slow vessel (60 % of observations at 4 km h⁻¹) but infrequently in encounters with a moderate vessel (22 % of observations at 11 km h⁻¹) and only rarely in encounters with a fast vessel (4 % of observations at 19 km h⁻¹). At all offset distances the proportion of flee responses decreased as speed increased, most notably for close encounters (Fig. 3). The relationship between frequency of flee responses and vessel speed was statistically significant for all except the widest offset category where it approached significance (Fig. 3).

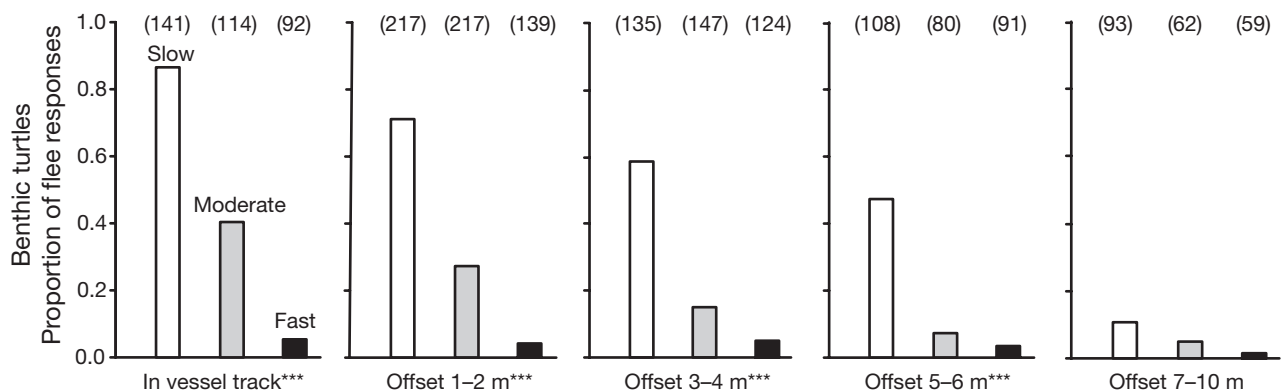


Fig. 3. *Chelonia mydas*. The proportion of turtles that fled from the approaching research vessel diminished as vessel speed increased; *** p < 0.001. White bars: vessel speed 4 km h⁻¹, grey bars: vessel speed 11 km h⁻¹, black bars: vessel speed 19 km h⁻¹. Number above each bar indicates total encounters (Flee + No Response; for definitions see 'Materials and methods: Data recording and analysis'). Offset value indicates lateral distance between turtle and vessel. Statistical data: offset 0 m: $\chi^2 = 152.6$, df = 2, p < 0.001; offset 1–2 m: $\chi^2 = 177.4$, df = 2, p < 0.001, offset 3–4 m: $\chi^2 = 111.4$, df = 2, p < 0.001; offset 5–6 m: $\chi^2 = 69.5$, df = 2, p < 0.001; offset 7–10 m: $\chi^2 = 5.3$, df = 2, p = 0.07

Effect of vessel speed on flight initiation distance

Vessel speed influenced the distance at which turtles initiated their response, if they responded at all. Turtles that fled in encounters with a slow vessel did so at a significantly greater distance (median FID 4.1 m, $n = 416$) than those that fled in encounters with moderate and fast vessels (median FID 2.2 m, $n = 157$, Mann-Whitney $U = 18516.5$, $p < 0.001$, Fig. 4a). Flee responses were pooled for fast and moderate speeds for this comparison as their flight initiation distances were not significantly different for these speeds (Mann-Whitney $U = 1192$, $p = 0.221$).

Effect of transit direction

During northbound transits turtles tended to flee more frequently and at slightly greater distances than during southbound transits. For all speed categories combined, on northbound transits 307 fled (35%) in 875 observations, with a median FID of 4.0 m, while on southbound transits 266 (28%) fled in 944 observations, with a median FID of 3.8 m. At slow speed, northbound, 220 (66%) fled in 333 observations with median FID 4.1 m, compared with slow speed southbound where 196 (54%) fled in 361 observations, with a median FID of 4.5 m. At slow speed, transit direction was associated with a significant difference in response frequency ($\chi^2 = 10.0$, $df = 1$, $p = 0.002$, Fig. 4b) and a marginally significant difference in flight initiation distance (Mann-Whitney $U = 19149$, $p = 0.049$). At moderate and fast speeds the differences were not statistically significant.

Non-benthic turtles

Encounters with non-benthic turtles (33 in the water column, 24 at the surface) followed the same general pattern as benthic turtles, showing reduced response frequency at faster vessel speed (Fig. 4c). The small sample sizes precluded further analysis.

Small turtles

Small turtle observations comprised 13 benthic turtles and 1 in the water column. Of the benthic turtles, 3 fled in 6 encounters at slow speed, 3 fled in 5 encounters at moderate speed, 1 fled in 2 encounters at fast speed. The small sample sizes precluded further analysis.

Response characteristics

All benthic turtles that responded to the vessel launched upwards at a shallow angle to the substrate and began swimming. Thereafter, individual turtles followed diverse trajectories, with 426 (74%) of the 573 that fled immediately moving away from the vessel's track, a 'safe' flee response as defined in Fig. 2b. However, 46 (8% of fleeing turtles) initially swam along the vessel's track ('in-track' response, Fig. 2c) and 101 (18% of fleeing turtles) crossed in front of the vessel before moving away ('cross-track' response, Fig. 2d).

In-track responses were slightly less frequent at slow speed (7%) than at moderate and fast speeds (both 10%). However, cross-track responses were more

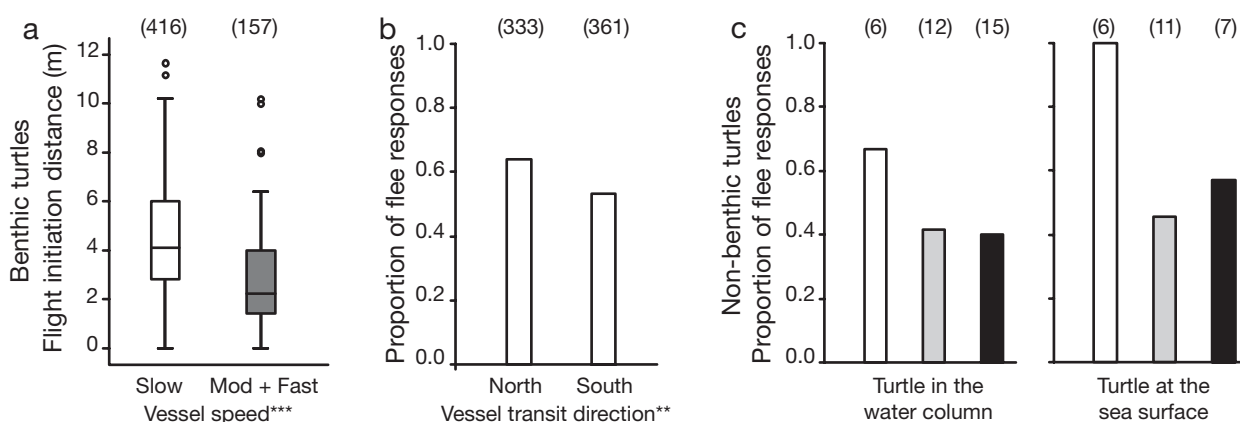


Fig. 4. *Chelonia mydas*. (a) Benthic turtles that fled in encounters with a slow vessel (4 km h^{-1}) had a significantly greater median flight initiation distance than those that fled in encounters with moderate (11 km h^{-1}) and fast (19 km h^{-1}) vessels, Mann-Whitney $U = 18516.5$, $p < 0.001$. Box plots show median, inter-quartile range, outliers and extreme cases. (b) Benthic turtles fled from a slow vessel more frequently when the vessel was heading north than when it was heading south ($\chi^2 = 10.0$, $df = 1$, $p = 0.002$). Northbound transits were expected to afford slightly enhanced underwater visibility—see 'Experimental trials'. (c) Turtles encountered at the sea surface fled more frequently than those in the water column, but small sample sizes precluded analysis by offset distances. White bars: vessel speed 4 km h^{-1} , grey bars: vessel speed 11 km h^{-1} , black bars: vessel speed 19 km h^{-1} . Number above each bar indicates total encounters (Flee + No Response). ** $p < 0.01$; *** $p < 0.001$

frequent at slow speed (20%) than moderate and fast speeds (11 and 10%, respectively). The majority of cross track responses, 80 (79%) of 101, involved a turtle that was initially located on the landward side of the vessel moving towards deeper water.

DISCUSSION AND CONCLUSIONS

Greater vessel speed increased the probability that turtles would fail to flee from the approaching vessel. Failure to flee leaves a turtle vulnerable to collision risk, unless adequate vertical distance between the vessel and the turtle allows the vessel to pass safely above the animal. Importantly, overwhelming failure to flee occurred at speeds slower than typical travelling speeds of contemporary vessels (see 'The role of vessel operators in avoiding collisions') and, as our results indicate, the majority of turtles cannot be relied upon to avoid vessels travelling faster than 4 km h⁻¹. Our findings thus imply that changes in human activity will be necessary to mitigate collision risks in areas where vessels operate in important turtle habitat.

Constraints on turtles' avoidance responses

The opportunity for an animal to respond appropriately to an approaching source of danger is necessarily constrained by how soon the animal can detect the danger. Contemporary knowledge of the sensory biology of marine turtles (Moein Bartol & Musick 2003) indicates that sound and light offer the only potential cues for detecting an approaching vessel. The ability of marine turtles to hear underwater sound has been confirmed by measuring their auditory brainstem responses (Ketten & Bartol 2006) and by observations of their behavioural responses to sound (O'Hara & Wilcox 1990, Moein et al. 1993). The relatively low frequency range of turtle hearing (Ketten & Bartol 2006) lies well within the broad frequency spectrum of noise produced by vessels (Richardson et al. 1995). Yet despite turtles' known auditory capacity, several factors mitigate against their reliance on sound cues.

The direction of an underwater sound source is difficult to identify precisely due to complex propagation characteristics of sound underwater (Richardson et al. 1995). In addition, marine areas heavily used by humans, such as Moreton Bay, are subject to noise from numerous vessels as well as other anthropogenic sources above and below the surface, which would tend to mask individual sounds. We infer that sound would have minimal utility for submerged turtles in identifying a mobile threat and suspect that turtles would tend to habituate to vessel sounds as back-

ground noise. Our results were consistent with this proposition. If turtles relied primarily on sound cues then higher response rates would be predicted for faster approaches (louder engine noise at higher speed), the converse of our results.

There appears to be no precedent in chelonian evolutionary experience for fast-moving noisy predators in the water. However, marine turtles have co-existed for millennia with swift, silent underwater predators. Sharks remain important predators of turtles in near-pristine coastal areas (see Heithaus et al. 2005) and early visual detection of an attacking shark would enable a turtle to enhance its survival prospects. We suggest that turtles depend similarly on timely visual detection to evade approaching vessels.

Efficient turtle vision has been confirmed through physiological and behavioural studies in the laboratory and on nesting beaches. This research has established that turtles see with sufficient visual acuity to discern relatively small (prey-sized) objects, differentiate between colours, and rely on vision for returning to the sea after nesting (see Moein Bartol & Musick 2003 and references therein). Retinal structures in turtles are considered likely to confer visual advantage in the marine environment (e.g. Oliver et al. 2000, Bartol & Musick 2001, Mäthger et al. 2007). Anecdotal field observations also attest to the apparent ability of turtles to detect danger by sight while underwater. For example, when the research vessel was anchored (with engine off) in the study area, green turtles were frequently observed moving slowly towards the vessel as they grazed on the substrate, but none passed close by or under the vessel. Instead, each approaching turtle altered course to maintain a distance of 15 to 20 m as it passed the silent vessel.

Underwater vision is limited in range because light transmission is attenuated by organic and inorganic matter in the water (Preisendorfer 1986). Consequently a submerged turtle that relies on visual detection of an oncoming vessel must be constrained by the prevailing water clarity. For example, if turtles' underwater vision slightly exceeds that of humans, a maximum visual detection limit of about 20 m would be likely in the clearest parts of Moreton Bay, whereas a range of hundreds of metres would be expected for auditory detection of a vessel motor (as is routinely confirmed by scuba divers), given that low frequency sounds propagate efficiently underwater (Richardson et al. 1995). The flight initiation distances for turtles that responded to our experimental vessel did not exceed 12 m (Fig. 3b), a finding consistent with dependence on visual cues rather than sound cues.

The difference in experimental response rates for northbound vs. southbound transits was also consistent with turtles' dependence on vision and water clarity.

Response rates were higher and flight initiation distances were slightly greater for northbound transits, when underwater visibility was enhanced by the direction of solar illumination (see 'Materials and methods'). This differential response by transit direction cannot be explained in terms of sound detection, since vessel heading did not alter engine noise.

The low rate of flee responses during moderate and fast experimental transits is consistent with physical limitations of visual detection. Simple calculation (time = distance/speed) shows that an optimistic scenario of a vessel approaching at 19 km h^{-1} in waters allowing 15 m visibility would provide only 3 s (Fig. 5) for a perpetually vigilant turtle to see the vessel, determine its trajectory and move out of its track. An even shorter response opportunity would apply if a turtle scans for danger only intermittently while it forages or rests, and if visibility is reduced by turbidity or darkness. We propose that the extreme brevity of response opportunity afforded to a vision-dependent turtle explains their inability to evade fast vessels.

The role of vessel operators in avoiding collisions

The moderate and fast speeds used in our experiment were lower than the speeds of many types of recreational and commercial vessels travelling across a large embayment like Moreton Bay. In non-planing displacement mode, small open water boats typically

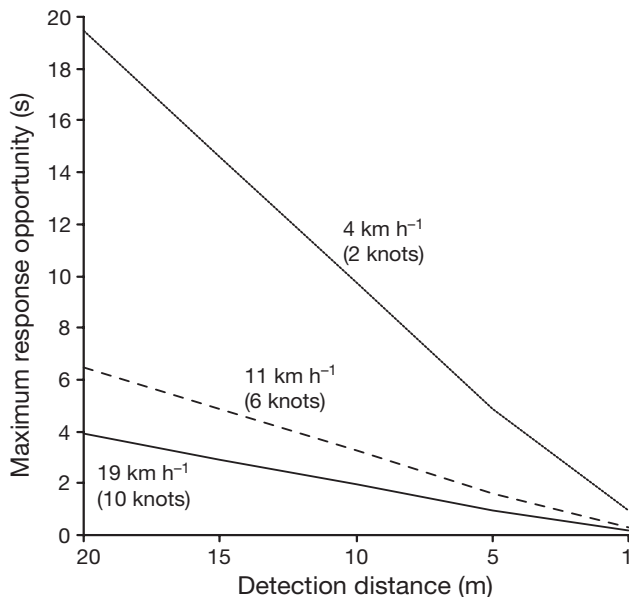


Fig. 5. *Chelonia mydas*. The theoretical maximum response opportunity time available to a perpetually vigilant turtle decreases with increasing vessel speed (plotted here for the 3 experimental speeds used in this study) and with decreasing detection distance

maintain 8 to 12 km h^{-1} and larger craft can travel correspondingly faster without planing. Planing vessels often exceed 20 km h^{-1} and many travel at 30 to 45 km h^{-1} , some even faster (Maitland et al. 2006, J. Hazel unpubl. data). Thus, most vessels travelling in unrestricted coastal waters maintain speeds that preclude reliable avoidance responses by turtles, and therefore collision avoidance must necessarily depend on vessel operators.

Stringent measures were employed during our experimental transits to ensure turtle safety: (1) a dedicated observer at the bow at all times, (2) travel restricted to high visibility conditions, (3) relatively low maximum speed, and (4) emergency stops when required. Comparable measures are seldom feasible for commercial and recreational vessels during normal operations. Choppy water and low light severely reduce the chance of sighting a turtle at the surface, while in turbid water even the most attentive observer cannot see submerged turtles. Turtles spend most of the time submerged—in our study 1866 out of 1890 encounters (99%) involved turtles below the surface—meaning that vessel operators will rarely be able to detect the close proximity of individual turtles. Even if a turtle is spotted at close range in front of a vessel, an immediate stop or abrupt course deviation will usually be impossible. Speed reduction appears to be the only way vessel operators can minimise collision risk when operating in turtle habitat.

Management considerations

Our results strongly support the use of speed restrictions to prevent vessel injuries to turtles in shallow waters. Given the diverse types of vessels that use relatively shallow areas, a minimum safe depth cannot be defined exactly but as a guiding principle, deeper water can be expected to reduce—but not eliminate—the risk of collisions. As demonstrated in our study, a vessel can pass safely over a benthic turtle provided there is sufficient clearance between the animal and extremities of the vessel, with allowance for water turbulence generated by hull movement and propeller rotation. Additional clearance is essential for safety because a turtle that detects the vessel only at the last moment is likely to move upwards, in initiating a belated flee response, just as the vessel passes over it, behaviour often noted during the experimental transits.

Our findings point to 2 situations where speed restrictions may be particularly valuable in protecting turtles: (1) where vessels travel across shallow turtle foraging habitat, and (2) where vessels use deeper channels between shoal banks that offer foraging op-

portunities for turtles. Deeper channels might be considered less risky on the criterion of depth alone. However, high volumes of vessel traffic adjacent to shallow foraging habitat may be particularly dangerous for turtles because of turtles' tendency to (1) flee towards deeper water (see 'Response characteristics' above) and (2) use deeper water to rest between foraging bouts during the day as well as overnight (e.g. Bjørndal 1980, Brill et al. 1995, Makowski et al. 2006). The collision risk for turtles in all areas is likely to be further exacerbated if water clarity is low and if vessel traffic continues at night, since both turbid water and darkness would impede turtles' visual detection of danger.

We note that optimal designation of speed restriction zones is a potentially complex task, especially for areas that host multiple vulnerable species. Some species may benefit from other mitigation measures (e.g. Gerstein 2002 advocates acoustic deterrents for manatees) and some sites may require a combination of speed and route restrictions (see recommendations of Maitland et al. 2006 for dugongs at Burrum Heads, Queensland).

The trade-off between minimising potential inconvenience to vessel operators and optimal protection for marine wildlife presents a challenge to managers, particularly as our results indicate that a very slow speed ($\sim 4 \text{ km h}^{-1}$) is necessary to assure a 'turtle-safe' transit across shallow foraging sites. Considering that vessel operators have long been accustomed to freedom of movement in coastal waters, it seems unlikely that the majority will voluntarily adopt substantially slower speeds. We believe that effective speed reduction will require mandatory measures backed by effective enforcement. Nevertheless, public education would be useful to raise awareness of the constraints on turtles' ability to evade vessels and increase vessel operators' understanding of collision mitigation measures.

If particular high-risk zones can be accurately identified, the most stringent enforceable speed constraint will maximise turtle safety. Enforcing stringent limits could provide further benefit by encouraging vessel operators to choose unrestricted alternative routes in deep water, where available. In addition to reducing collision risk, such choices should also reduce potential non-lethal disturbance of foraging and resting animals.

If vessels divert around speed-restricted zones, management measures should also address additional risks that arise from vessels travelling at high speed close to zone boundaries which follow the margins of a shallow area (for example, Go-Slow zones in Moreton Bay are nominally defined by the 2-m depth contour). In close encounters near a shallow boundary, turtles are more likely to flee across the vessel's track towards adjacent deeper water. This risk could be alleviated by ensuring speed-restricted zones include broad safety margins

around the shallow expanses they are designed to protect. Such safety margins could also benefit other species vulnerable to vessel collisions, since deeper water probably represents safe refuge for dugongs (Hodgson & Marsh 2007), and manatees have been observed to turn towards the nearest deep water when boats approach (Nowacek et al. 2004).

Long term risk mitigation

Individual green turtles are known to maintain long-term fidelity to their coastal foraging areas, with only brief absences during breeding migrations spaced several years apart (Limpus et al. 1992, 1994). Thus for each individual turtle in a foraging area that receives vessel traffic, the risk of collision persists over decades. For turtles, the cumulative risk of collision is high and the likely consequence, in the event of collision, is severe injury or death. With vessel numbers likely to increase over time, the risk for turtles must continue to escalate in future unless vessel speed can be effectively reduced.

Our informal discussions with many local vessel operators have established that operators seldom assess cumulative risk and usually make operational decisions in terms of immediate risk. They quite reasonably assume a very low probability of collision with a turtle during a single voyage. Furthermore, they anticipate no harm to personnel and little or no damage to the vessel from a collision with a turtle. Therefore, from a vessel operator's perspective, there is no self-interest in supporting voluntary speed reduction. Consequently, we conclude that mitigation of risk for turtles must depend on management intervention. Compulsory speed limits, underpinned by effective enforcement measures, appear essential if turtles are to be protected in key habitats subject to vessel traffic.

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