APPENDIX 9B: PARTICLE MOTION

INTRODUCTION

1.1. This document has been produced in order to respond to the Scoping Opinion received from Marine Scotland Licencing and Operations team (MS-LOT) (See Table 1.1 below). The Scoping Report set out the approach to the EIA for the optimised Seagreen Project, specifying which receptors and impacts should be considered.

Table 1.1 Scoping Opinion received from MS-LOT

Section	Comment
11.4.1	Since the ES for the Seagreen Original Development was produced there has been a considerable increase in the relevant literature which suggests that there is potential for impacts from acoustic particle motion on fish and invertebrates. An issue that has been raised by MSS at the scoping meetings is the need to consider potential impact of acoustic particle motion on sensitive receptors in addition to the effects of sound pressure on fish species that are sensitive to this.
11.4.2	There is acknowledgement that understanding of the effects from particle motion, and extent of these effects, is currently an area for further development, and there are various initiatives being progressed. Marine Scotland Science (MSS) considers that the currently available evidence suggests that particle motion could be an important mechanism of effect on fishes and invertebrates. As the 2017 EIA Regulations require the Scottish Ministers to come to a reasoned conclusion on the significant effects on the environment of the development, based on up to date information, this information needs to be taken into account. MSS provided a list of the following references (Extracted from Appendix 5 of the Scoping Opinion): • Ceraulo, M., Bruintjes, R., Benson, T., Rossington, K., Farina, A. and Buscaino, G. (2016) Relationships of underwater sound pressure and particle velocity in a shipbuilding dock. In: 4th International Conference on The Effects of Noise on Aquatic Life, 10-16 July 2016, Dublin, Ireland. • Farcas, A., Thompson, P. M., & Merchant, N. D. (2016). Underwater noise modelling for environmental impact assessment. Environmental Impact Assessment Review, 57, 114-122. • Harding, H, Bruintjes, R, Radford AN Simpson SD (2016) Measurement of Hearing in the Atlantic salmon (Salmo salar) using Auditory Evoked Potentials, and effects of Pile Driving Playback on salmon Behaviour and Physiology Scottish Marine and Freshwater Science Report Vol 7 No 11 • Hawkins, A. and Popper, A. (2016). A Sound Approach to Assessing the Impact of Underwater Noise on Marine Fishes and Invertebrates. ICES Journal of Marine Science, 74(3), 635-651. • Mueller-Blenkle, C., McGregor, P.K., Gill, A.B., Andersson, M.H., Metcalfe, J., Bendall, V., Sigray, P., Wood, D.T. & Thomsen, F. (2010) Effects of Pile-driving Noise on the Behaviour of Marine Fish. COWRIE Ref: Fish 06-08, Technical Report 31st March 2010 • Nedelec, S. L., Campbell, J., Radford, A. N., Simpson, S. D., and Merchant, N. D. 2016. Particle motion: the missing link in underwater acoustic ecology. Methods in Ecology and Evolution, 7, 836–842. • Normandeau Associates, Inc. (2012). Principal authors Anthony D. Hawkins and Arthur N. Popper. Effects of Noise on Fish, Fisheries, and Invertebrates in the U.S. Atlantic and Arctic from Energy Industry Sound-Generating Activities. A Literature Synthesis for the U.S. Dept. of the Interior, Bureau of Ocean Energy Management. Contract # M11PC00031. 153 pp. • Popper A. N., and Hastings M.C. (2009) The effects of anthropogenic sources of sound on fishes Journal of Fish Biology (2009) 75, 455–489 (general review of sound and fish with useful insights on pile driving and particle motion) • Popper, A. N., and Hawkins, A. D. (2016). The effects of noise on aquatic life, II. Springer Science & Business Media, New York.

Section	Comment
	• Popper, A. N., Hawkins, A. D., Fay, R. R., Mann, D. A., Bartol, S., Carlson, T. J., Coombs, S., et al. 2014. Sound Exposure Guidelines. In ASA S3/SC1. 4 TR-2014 Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI, pp. 33–51. Springer, New York. • Radford, CA, Montgomery, JC, Caiger P and Higgs DM (2012) Pressure and particle motion detection thresholds in fish: a re-examination of salient auditory cues in teleosts. The Journal of Experimental Biology 215, 3429-3435 • Roberts L and Elliott M (2017) Good or bad vibrations? Impacts of anthropogenic vibration on the marine epibenthos. Science of the Total Environment 595:255-268. • Roberts, L. (2015). Behavioural responses by marine fishes and macroinvertebrates to underwater noise (Doctoral dissertation, University of Hull). • Robinson, S.P., Lepper, P. A. and Hazelwood, R.A. (2014) Good Practice Guide for Underwater Noise Measurement. NPL (National Physical Laboratory) Good Practice Guide No. 133. http://www.npl.co.uk/upload/pdf/gpg133-underwater-noise-measurement.pdf • Sigray, P. and Andersson, M. (2011). Particle Motion Measured at an Operational Wind Turbine in Relation to Hearing Sensitivity in Fish. Journal of the Acoustical Society of America, 130(1), 200-207 • Spiga I, Caldwell GS and Bruintjes R. (2016) Influence of Pile Driving on the Clearance Rate of the Blue Mussel, Mytilus edulis (L.). In: Fourth International Conference on the Effects of Noise on Aquatic Life. 2016, Dublin, Ireland: Acoustical Society of America. • Thomsen, F., Gill, A., Kosecka, M., Andersson, M. H., Andre, M., Degraer, S., & Norro, A. (2015). MaRVEN–Environmental Impacts of Noise, Vibrations and Electromagnetic Emissions from Marine Renewable Energy. Final study report., Brussels, Belgium. • Zhang, Y, Shi F, Song J, Zhang X and Yu S (2015) Hearing characteristics of cephalopods: Modeling and environmental impact study. Integrative Zoology 10 (1) 141–151 http://onlinelibrary.wiley.com/doi/10.1111/1749-4877.12104/full
11.4.3	MSS suggests that Seagreen takes the following approach: • Provide an overview of currently available information on particle motion within the vicinity of noise producing construction and operational activities, including, for example, pile driving, dredging and explosions – both within the water column and the sea bed. This should include consideration of the likely distances at which elevated levels of particle motion may be detected. • Provide an overview of the published information on sensitive species and potential physiological and behavioural effects of particle motion. • Give consideration to the potential effects of particle motion on species known to occur around the Revised Development (Seagreen: optimised Seagreen Project) site, making use of information on species distribution from the Original Development (Seagreen: original Offshore) ES and information which has become available since then. Particular attention should be given to potential effects on species of commercial or conservation concern. • Provide information on opportunities that the Revised Development (Seagreen: optimised Seagreen Project) may present to investigate effects of particle motion on fish and invertebrates.
11.4.4	The Scottish Ministers agree that the potential impact of particle motion should be assessed and suggests that Seagreen follows the approach outlined by MSS.

Purpose of this Document

1.2. This document aims to address the comments raised by Marine Scotland Science (MSS) and Scottish Ministers on the Natural Fish and Shellfish section of the 2017 Scoping Report for the optimised Seagreen Project by undertaking a review of the documents identified by MSS on particle motion, as well as other relevant publications as identified.

1.3. The comments from both MSS and Scottish Ministers largely relate to new evidence concerning particle motion which has been published since the submission of the Original Offshore ES in 2012 or its preparation over the preceding period. The comments reflect the fact that underwater noise propagation models applied in EIAs have considered only the sound pressure component of underwater noise and assessments have generally not considered particle motion effects to any extent. Particle motion is increasingly recognised as a potentially important mechanism for effects relating to offshore developments such as wind energy, especially for those fish species more sensitive to particle motion than sound pressure (Farcas et al., 2016), and to invertebrates which are only sensitive to particle motion (Miller et al., 2016; Roberts & Breithaupt, 2016).

REVIEW OF LITERATURE

Particle motion

1.4. The passage of a sound wave underwater causes oscillatory pressure changes as vibrating particles cause alternate rarefaction and compression. Detection of hydrostatic pressure changes forms the basis of marine mammal and some fish hearing systems and is also how sound is measured with hydrophones. However, it is the particle motion component which is the mechanism through which many organisms, including invertebrates and all fish, detect sound (Popper and Fay, 2011). This vibration is not distinct from underwater sound or noise, but rather the particle motion component of it.

1.5. Whereas sound pressure is only propagated through the water column, particle motion can also propagate through the seabed. Vibrations within seabed sediments will occur as a result of the physical interaction between the monopile and the seabed and substrate-borne particle motion may propagate further from the source than through the water column and may also enter the water column at distance from the source (Roberts & Breithaupt, 2016).

1.6. In certain conditions particle motion (expressed as particle velocity (ms^{-1}), particle acceleration (ms^{-2}) or particle displacement (m)) can be calculated from the sound pressure; however, this requires the sound to be a plane wave, i.e. the wave front is flat and not influenced by boundary reflections from the seabed. This condition is therefore generally not met in coastal environments and measurement of particle motion, rather than calculation from sound pressure, should generally be considered where water depths are less than 100m (Nedelec et al., 2016). The same authors point out that equipment to measure particle displacement directly in the marine environment, has only recently become commercially available and as a corollary that there is a growing, but still limited, understanding of the importance of particle motion and its potential to influence the behaviour, physiology and development of organisms. Likewise, there is very limited information about the magnitude of particle displacement to be expected from offshore wind turbine foundation piling and a lack of information from measurements of particle motion.

1.7. Martin et al. (2016), cited in Nedelec et al. (2016), state that there are three main methods of measuring particle motion underwater: (i) calculating the pressure gradient between two hydrophones; (ii) measuring with velocity sensors; and (iii) measuring with accelerometers. They note that ‘Velocity sensors (geophones) typically have a very low resonance and are only useful up to a few tens of Hertz. While geophones make better sensors for seismic measurements, accelerometers are more appropriate for acoustic measurements.’ There is a general lack of consensus on the approach to measuring particle motion in relation to offshore wind energy and other developments and a lack of data from in situ recordings (Farcas et al., 2016; Merchant et al., 2015).

Anthropogenic sources

Pile-driving

1.8. There are very limited data relating to particle motion levels resulting from pile-driving during the installation of offshore wind farm foundations. Measurements were collected by Thomsen et al. (2015) during the construction of an offshore wind farm in the southern North Sea; particle motion was considered to be sufficiently elevated above ambient levels within 750m of piling locations, across most of the frequency spectrum, to be detectable by most fish species.

1.9. Other studies relating to particle motion resulting from piling have been conducted in tanks (Ceraulo et al., 2016; Harding et al., 2016; Spiga et al., 2016) and/or using recordings, played-back with speakers to replicate piling noise (Martin et al., 2016; Roberts, 2015; Harding et al., 2016). These studies need to be interpreted with caution but are informative, especially in relation to the attenuation of particle motion with distance from source which has consistently been demonstrated to be rapid. For example, Mueller-Blenkle et al. (2010) demonstrated a rapid attenuation of particle motion up to 30m from a sound play-back source and slower reduction beyond that distance.

Operational turbines

1.10. Thomsen et al. (op. cit.) also measured the differing levels of particle motion around operational wind turbines. Levels were found to be measurably greater than background within 40m of the turbine base, and emissions from steel monopile foundations were noted to be greater than those from jacket-based turbines. These results were not related to audibility to marine fauna.

Particle motion sensitivity in Fish

1.11. All fish detect sound, but the manner in which they do so varies. Those species possessing a swim bladder may use the volume changes in the bladder induced by passage of a sound pressure wave to induce particle motion which is subsequently detected by their hearing system. Fish without a swim bladder can only detect particle motion directly. Particle motion detection thus underpins fish hearing, whether or not a particular species is sensitive to sound pressure. All teleost fish species are believed to have a similar ability to detect the particle motion component of underwater sound, inter-specific variability is thought to relate to the use of ancillary structures (e.g. swim bladder) to convert sound pressure into particle motion (Radford et al., 2012) and is at least partly related to the distance and connection between the anterior part of the swim bladder and inner ear (Popper and Fay, 2011).

1.12. Elasmobranchs also detect particle motion although those species studied have been reported to be less sensitive than teleost fish (Casper et al., 2012).

1.13. Fish primarily detect particle motion via the otolith, a sensory organ within the inner ear. It is a calcium carbonate structure, far denser than other tissues within the animal and as such, the otolith moves differently relative to the rest of the body in the presence of sound waves. Sensory hair cells surrounding the otolith can then detect these displacements (Hawkins & Popper, 2017; Roberts, 2015; Martin et al., 2016). Where there is a connection between the swim bladder and inner ear, such as in herring and other clupeids, the fish is likely to be relatively sensitive to underwater noise because of the greater propagation of sound pressure underwater, compared to particle displacement through water, or sediment and the fishes ability to convert this sound pressure into particle displacement.

1.14. Some fish species, such as salmonids, although possessing a swim bladder, are not sensitive to sound pressure because there is a lack of connection between the swim bladder and inner ear. Such species are able to detect only the particle motion component of noise (Mueller-Blenkle et al., 2010; Hawkins & Popper, 2016 & 2017).

1.15. A secondary means by which fish can detect particle motion is the lateral line (Fay & Popper, 2000). These are sensory epithelial cells which run along the body and can detect vibration and pressure changes nearby. Used for prey detection and predator avoidance in the near-field, it is considered that the lateral line system is most effective in the detection of particle motion over short ranges (Roberts, 2015).

1.16. The variation in the manner of sound detection between fish species, led Popper et al. (2014) to classify fish into three categories:

Type 1: Fish without a swim bladder or any other gas filled body cavities. These species are considered to be sensitive only to particle motion and include flatfish species, elasmobranchs, mackerel and sandeels.

Type 2: Fish possessing swim bladders, or other gas filled body cavities which are not involved in hearing. Examples include salmonids. Such species are also considered only to be sensitive to particle motion. They may however be vulnerable to physical injury resulting from very high sound pressure levels if these damage their swim bladder.

Type 3: Fish with swim bladders, or other gas filled body cavities which are involved in hearing. These species are considered to be sensitive to both particle motion and sound pressure and include gadoids (e.g. cod and haddock) and clupeids (e.g. herring and sprat). Due to their ability to detect the pressure component of underwater noise, the frequency sensitivity ranges of these species and their acuity levels are greater, hence this group is frequently referred to as the 'hearing specialists'.

Particle motion sensitivity in Shellfish

1.17. Invertebrates, lacking swim bladders or other air filled spaces, are not considered to be sensitive to sound pressure (Mooney et al., 2010 & 2012). The understanding of marine invertebrate sensitivity to particle motion is in its infancy (Lewandowski et al., 2016) and very little information is available on hearing capabilities.

1.18. It is believed that marine invertebrates only detect particle motion at low frequencies (Mooney et al., 2010 & 2012) and has been reported that invertebrates generally appear to be rather less sensitive to particle motion than fish (Roberts & Elliot, 2017; Fay & Simmons 1998). Thomsen et al. (2015), noted that elevations in particle motion levels recorded 750m from a piling operation, considered to be detectable by fish, were unlikely to be detectable by marine invertebrates.

1.19. Crustacea, such as *Nephrops norvegicus*, are believed to detect particle motion via mechano-receptors which include: internal statocysts (a fluid filled chamber containing a relatively dense material (statolith) surrounded by sensory hair cells which may be analogous to the otolith in fish); chordontal organs (ciliated stretch receptors acting as proprioceptors in insects and Crustacea which may also have a role in detecting particle motion); and superficial surface receptors (Cavlie and Albert, 2013; Roberts & Elliot, 2017).

1.20. Roberts and Breithaupt (2016) provide a review of the sensitivity of crustaceans to substrate-borne vibration. They noted greatest sensitivity at frequencies below 200 Hz which corresponded to the expected frequency from activities such as pile-driving. The same authors suggest that any ability to detect noise due to activities such as piling is likely to be possible via the water-borne pathway only very close to the source, and potentially to a greater distance via the seabed, because of the more efficient propagation of sound in this manner.

1.21. Receptor systems in molluscs remain relatively unstudied, therefore the potential detection of particle motion in this group are poorly understood (Roberts & Elliot, 2017). Molluscs such as squid (Cephalopoda) use a sensory receptor organ known as a statocyst in the same manner as Crustacea (Kaifu et al., 2008). A number of bivalves may possess additional sensory organs, such as the abdominal organ in scallops, which are understood to be highly sensitive to water-borne vibrations (Zhadan, 2005). This would suggest sensitivity at close range to activities such as piling.

1.22. A review of cephalopod response to sound by Samson et al. (2016) suggests sensitivity between around 1 and 300Hz, but with significantly higher upper limits in some species such as the common octopus (*Octopus vulgaris*).

1.23. Substrate-borne particle motion is likely to be most relevant to underwater noise detection for benthic molluscs such as bivalves (Roberts & Elliot, 2017).

Potential Effects of Particle Motion

1.24. Underwater noise, comprising sound pressure and particle displacement, has at least theoretical potential to have a number of effects on fish and shellfish, depending upon the magnitude and character of the sound source and its propagation to receptor organisms. Effects can range from mortality, physical injury and temporary or permanent hearing impairment, to influences upon behaviour (Knight & Swaddle, 2011). Physical effects such as injury associated with high sound pressures are well known in animals possessing gas filled spaces such as swim bladders where barotrauma can result in tissue damage. Whilst tissue damage has been postulated for extreme levels of particle displacement there is no confirmed evidence of such effects (Popper et al., 2014) and animals lacking swim bladders are understood to be less vulnerable to such effects than those with swim bladders.

1.25. A study by Zhang et al. (2015) modelled the auditory capabilities of cephalopods and suggested that severe particle motion could irreparably damage the statocyst at short range, causing hearing impairment. This could be associated with high intensity events such as pile driving, but effects would only be expected at very short range.

1.26. Behavioural effects are more complex to identify, interpret and assess. Most studies have been conducted on animals in captivity and Popper et al. (2014) caution that care should be taken in inferring implications for animals in the wild, especially when coupled with the challenges associated with measuring particle displacement in the marine environment.

1.27. Mueller-Blenkle et al. (2010) used play-back recordings of pile driving noise to investigate the response of fish within artificial mesocosms (large submerged netted enclosures), in a Scottish sea loch. The swimming behaviour of sole (*Solea solea*), which lack a swim bladder and are therefore assumed able to detect only the particle displacement component of underwater noise, was observed and an initial avoidance reaction and increased swimming speed recorded. Because of the pronounced decrease in particle motion over the first 30m it was suggested that the ability to detect particle motion is likely to be restricted to a relatively small area around a sound source, even under natural conditions.

1.28. Evidence of behavioural responses in the marine environment is inconsistent. Roberts (2015) used play-back pile-driving noise in an Irish sea lough and observed that shoals of free-swimming Atlantic mackerel (*Scomber scombrus*) responded by scattering and changing depth; in contrast, a large shoal of mackerel which had gathered around a foundation installation vessel did not respond in any noticeable manner to pile driving, as this took place intermittently over a period of several days (NIRAS, pers. obs.).

1.29. In a laboratory study Harding et al. (2016) reported that Atlantic salmon did not perceive played-back recordings of pile driving as a stressor and showed no evidence of any startle response. Equivalent conclusions were drawn by Nedwell et al. (2003) from experiments using caged brown trout (*Salmo trutta*) placed around pile driving locations at the red funnel facility in Southampton.

1.30. Hawkins and Popper (2017) note that for hearing specialist fish where the swim bladder is connected to the hearing system, both pressure and particle motion components of underwater noise are likely to be processed simultaneously. This may allow such species to develop a more complex understanding of their acoustic environments than species utilising only particle motion.

1.31. Information on the importance of underwater noise for marine invertebrates remains very limited, but interest in this area is developing. Roberts (2015) suggested that vibroacoustic stimuli may elicit and affect anti-predator responses, such as startle response in crabs and valve closure in mussels. Such responses would effectively be distractions from routine activities such as feeding.

1.32. In mussels, increased filtration rates are hypothesised to occur as a result of increased energetic demand, as a consequence of a physiological stress response to substrate-borne particle motion produced by piling. Spiga et al. (2016), observed blue mussels to increase the rates at which they removed suspended particles from the water column in response to simulated pile-driving. Samson et al. (2016) recorded a range of behavioural responses to underwater noise in cephalopods, including inking, colour changes and startle responses.

SUMMARY

1.33. Whilst knowledge on the importance of the particle displacement component of underwater noise for fish and shellfish is relatively limited, the following general conclusions are drawn from the above information:

- All fish species are understood to have the ability to detect the particle displacement component of underwater sound. This suggests the potential for behavioural effects from high energy activities such as pile driving;
- For fish with a swim bladders, behavioural effects mediated by sound pressure changes are likely to be more important than particle displacement at any distance beyond very close range to the sound source;
- For fish lacking a swim bladder, or for those species where the swim bladder is not connected to the hearing system, behavioural effects are expected to be restricted to a close range from the sound source (e.g. tens to low hundreds of metres from piling);
- Marine invertebrates are understood to be potentially sensitive only to particle displacement (not sound pressure);
- Marine invertebrates are believed to be *relatively* insensitive to underwater noise compared to fish, but the potential exists for behavioural effects at close range (e.g. tens of metres);

- Physical injury and mortality effects due to particle displacement are not anticipated for either fish or invertebrates, although evidence in this area is restricted and there may be a theoretical risk at very close range to piling.

1.34. The Scoping Opinion from Marine Scotland Science also suggests that Seagreen 'provide information on opportunities that the Revised Development (Seagreen: optimised Seagreen Project) may present to investigate the effects of particle motion on fish and invertebrates.' This matter should be discussed further with Marine Scotland Science following further project development work, not least to confirm detailed wind turbine generator foundation design and any requirement for pile driving. The issue is one which extends beyond the individual project, or even industry level, in that particle displacement effects are potentially relevant to all offshore wind developments and to other noise-generating offshore activities, such as seismic survey. In this respect it is hoped that a collaborative approach to any research and development orientated work could be adopted.

1.35. Any study would require careful consideration of appropriate methods, particularly the measurement of underwater noise, given the lack of consensus on the approach to measuring particle motion in relation to offshore wind energy as previously noted.

REFERENCES

Andriguetto-Filhoa J.M., Ostrenskya A., Pieb M.R., Silvac U.A. and Boeger W.A. (2005) Evaluating the impact of seismic prospecting on artisanal shrimp fisheries. Continental Shelf Research 25:1720-1727.

Carlson T.J. (2012) Barotrauma in fish and barotrauma metrics. In: Popper A.N. and Hawkins A.D. (Eds) The effects of noise on aquatic life. Springer Science + Business Media, LLC, New York, 229–234.

Casper B. M., Halvorsen M. B. and Popper A. N. (2012) Are sharks even bothered by a noisy environment? In The Effects of Noise on Aquatic Life, pp. 93–97. Ed. by A., Hawkins, A. N., Popper Springer, New York.

Cavlie RV and Albert JT (2013) Chordotonal organs. Current Biology: 23, Issue 9, pR334–R335, 6 May 2013.

Ceraulo M., Bruintjes R., Benson T., Rossington K., Farina A. and Buscaino G. (2016) Relationships of underwater sound pressure and particle velocity in a shipbuilding dock. In: 4th International Conference on the Effects of Noise on Aquatic Life, 10-16 July 2016, Dublin, Ireland.

Farcas A., Thompson P.M. and Merchant N.D. (2016). Underwater noise modelling for environmental impact assessment. Environmental Impact Assessment Review, 57, 114-122.

Fay R.R. and Simmons A.M. (1998) The sense of hearing in fish and amphibians. In: Fay, R.R., Popper, A.N. (Eds.), Comparative Hearing: Fish and Amphibians. Springer, New York, pp. 269–318.

Harding H., Bruintjes R., Radford A.N. and Simpson S.D. (2016) Measurement of Hearing in the Atlantic salmon (Salmo salar) using Auditory Evoked Potentials, and effects of Pile Driving Playback on salmon Behaviour and Physiology Scottish Marine and Freshwater Science Report Vol 7 No 11.

Harris, G. G., and van Bergeijk, W. A. (1962). "Evidence that the lateral line organ responds to near-field displacements of sound sources in water," J. Acoust. Soc. Am. 34, 1831–1841

Hawkins A.D. and Popper A.N. (2016) Developing Sound Exposure Criteria for Fishes. In Popper A.N., and Hawkins A.D. The effects of noise on aquatic life, II. (pp. 431 -440). Springer Science+Business Media, New York.

Hawkins A. and Popper A. (2017). A Sound Approach to Assessing the Impact of Underwater Noise on Marine Fishes and Invertebrates. ICES Journal of Marine Science, 74(3), 635-651.

Kaifu K., Akamatsu T. and Segawa S. (2008) Underwater sound detection by cephalopod statocyst. Fish Sci 74:781–786.

Knight C.R. and Swaddle J.P. (2011) How and why environmental noise impacts animals: an integrative,mechanistic review. Ecol Lett.

Lewandowski J., Luczkovich J., Cato D. and Dunlop R. (2016) Summary Report Panel 3: Gap Analysis from the Perspective of Animal Biology: Results of the Panel Discussion from the Third International Conference on the Effects of Noise on Aquatic Life. In Popper A.N. and Hawkins A.D. The effects of noise on aquatic life, II. (pp. 1277 - 1282). Springer Science+Business Media, New York.

Martin B., Zeddies D.G., Gaudet B. and Richard J. (2016) Evaluation of Three Sensor Types for Particle Motion Measurment. In Popper A.N., and Hawkins A.D. The effects of noise on aquatic life, II. (pp. 679 - 687). Springer Science+Business Media, New York.

Merchant N.D., Fristrup K.M., Johnson M.P., Tyack P.L., Witt M.J., Blondel P. and Parks S.E. (2015) Measuring acoustic habitats. Methods in Ecology and Evolution, 6, 257-265.

Miller J.H., Potty G.R. and Kim H.K. (2016) Pile-Driving Pressure and Particle Velocity at the Seabed: Quantifying Effects on Crustaceans and Groundfish. In Popper A.N., and Hawkins A.D. The effects of noise on aquatic life, II. (pp. 719 - 729). Springer Science+Business Media, New York.

Mooney T.A., Hanlon R.T., Christensen-Dalsgaard J., Madsen P.T., Ketten D.R. and Nachtigall P.E. (2010) Sound detection by the longfin squid (Loligo pealeii) studied with auditory evoked potentials: Sensitivity to low-frequency particle motion and not pressure. Journal of Experimental Biology 213:3748-3759.

Mooney T.A., Hanlon R.T., Madsen P.T., Christensen-Dalsgaard J., Ketten D.R. and Nachtigall P.E. (2012) Potential for sound sensitivity in cephalopods. In: Popper A.N. and A.D. Hawkins (Eds). The effects of noise on aquatic life. New York: Springer Science + Business Media, LLC. pp. 125-218.

Mueller-Blenkle C., McGregor P.K., Gill A.B., Andersson M.H., Metcalfe J., Bendall V., Sigray P., Wood D.T. and Thomsen F. (2010) Effects of Pile-driving Noise on the Behaviour of Marine Fish. COWRIE Ref: Fish 06-08, Technical Report 31st March 2010.

Nedelec, S. L., Campbell, J., Radford, A. N., Simpson, S. D., and Merchant, N. D. (2016). Particle motion: the missing link in underwater acoustic ecology. Methods in Ecology and Evolution, 7, 836 842. http://onlinelibrary.wiley.com/doi/10.1111/2041-210X.12544/pdf

Nedwell J.R., Langworthy J. and Howell D. (2003) Assessment of sub-sea acoustic noise and vibration from offshore wind turbines and its impact on marine wildlife; initial measurements of underwater noise during construction of offshore windfarms, and comparison with background noise. Report 544R0424, prepared by Subacoustech Ltd., Southampton, UK, for Collaborative Offshore Wind Research into the Environment (COWRIE), May 2003

Popper, A.N., Fay, R.R., (2011). Rethinking sound detection by fishes. Hear. Res. 273, 25–36.

Popper A.N., and Hawkins A.D. (2018). The importance of particle motion to fishes and invertebrates. The Journal of the Acoustical Society of America 143, 470 (2018); doi: 10.1121/1.5021594

Popper A.N., Hawkins A.D., Fay R.R., Mann D.A., Bartol S., Carlson T.J., Coombs S., et al. (2014) Sound Exposure Guidelines. In ASA S3/SC1. 4 TR-2014 Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI, pp. 33–51. Springer, New York.

Radford C.A., Montgomery J.C., Caiger P. and Higgs D.M. (2012) Pressure and particle motion detection thresholds in fish: a re-examination of salient auditory cues in teleosts. The Journal of Experimental Biology 215

Roberts L. (2015) Behavioural responses by marine fishes and macroinvertebrates to underwater noise (Doctoral dissertation, University of Hull).

Roberts L. and Breithaupt T. (2016) Sensitivity of Crustaceans to Substrate- Borne Vibration. In Popper A.N., and Hawkins A.D. The effects of noise on aquatic life, II. (pp. 925 - 932). Springer Science+Business Media, New York.

Roberts L. and Elliott M. (2017) Good or bad vibrations? Impacts of anthropogenic vibration on the marine epibenthos. Science of the Total Environment 595:255-268.

Samson JE, Mooney TA, Gussekloo SWS and Hanlon RT (2016) A Brief Review of Cephalopod Behavioral Responses to Sound. In Popper A.N., and Hawkins A.D. The effects of noise on aquatic life, II. (pp. 969 - 976). Springer Science+Business Media, New York.

Spiga I., Caldwell G.S. and Bruintjes R. (2016) Influence of Pile Driving on the Clearance Rate of the Blue Mussel, Mytilus edulis (L.). In: Fourth International Conference on the Effects of Noise on Aquatic Life. 2016, Dublin, Ireland: Acoustical Society of America.

Thomsen F., Gill A., Kosecka M., Andersson M.H., Andre M., Degraer S. and Norro A. (2015) MaRVEN–Environmental Impacts of Noise, Vibrations and Electromagnetic Emissions from Marine Renewable Energy. Final study report. Brussels, Belgium.

Thomsen F, Lüdemann K, Kafemann R, Piper W (2006) Effects of offshore wind farm noise on marine mammals and fish, biola, Hamburg, Germany on behalf of COWRIE Ltd, Newbury, UK

van Bergeijk, W. A. (1964). "Directional and nondirectional hearing in fish," in Marine Bio-acoustics, edited by W. A. Tavolga (Pergamon, New York), pp. 281–299.

Zhadan P.M., (2005) Directional sensitivity of the Japanese scallop Mizuhopecten yessoensis and swift scallop Chlamys swifti to water-borne vibrations. Russ. J. Mar. Biol. 31, 28–35.