Extremely loud and incredibly close: *in situ* exposure of Atlantic cod to pile driving

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Underwater noise related to human activities is an increasing source of pollution in the marine environment. Although offshore wind farms (OWFs) do create green energy, they adversely affect the marine ecosystem by introducing different types of underwater noise. Especially during the construction phase, high impulsive sound is generated when the steel foundation piles are driven into the sea bottom. Impulsive underwater noise can be detrimental for marine life. Several laboratory experiments on fish and marine mammals showed behavioral changes, physiological stress, internal and external injuries, sometimes leading to mortality. However, a recent *in situ* study in the Belgian part of the North Sea (BNS) only showed short term physiological effects in larval and juvenile seabass (*Dicentrarchus labrax*) after exposure to high impulsive sound in the direct vicinity (<50 m) of a real pile driving event. Still, during that field experiment adult whiting (*Merlangus merlangus*) was seen floating at the surface at the moment of pile driving. Next to the need to further determine solid sound thresholds to be used in international guidelines, this anecdotic observation was the immediate reason for the current *in situ* experiment. In the summer of 2016, a field experiment was undertaken in the Nobelwind OWF on the BNS, to determine the direct effect of pile driving on the health status of Atlantic cod (*Gadus morhua*). Cod is classified as a vulnerable species on the IUCN list, it has a closed swim bladder (physoclistous fish) which makes it more vulnerable to swim bladder injuries, and it is known to aggregate around OWFs in the BNS. Large netted cages, each holding 10 cod individuals (avg. size 30 cm), were submerged at 8 m under the water surface. The cages were placed at increasing distances (75 m, 400 m, 1400 m and 1700 m) from the sound source, being the offshore installation vessel *Vole au vent*. All cages were submerged for on average 16 hours before pile driving, after which all fish were exposed to one pile driving event (lasting on average 2 hours). A similar control experiment was repeated in the same period when no pile driving took place. Underwater noise levels were measured at different distances during pile driving, while background measurements were made to determine ambient noise levels. Average single strike sound exposure levels (SEL_{ss}) decreased from 181 dB re 1µPa²s at 100 m distance to 168 dB re 1µPa²s at 1700 m distance. Ambient sound pressure levels (SPL) varied between 114 and 138 dB re 1µPa.

On average, 28 hours after exposure, the cages were retrieved onboard RV Simon Stevin, and all cod individuals were evaluated for buoyancy in water tanks. Shortly afterwards, all fish were euthanized and examined for swim bladder barotrauma and internal bleeding. Overall, 11 % cod were retrieved death, most probably due to handling stress, as no direct relation could be found with distance to the sound source. On the other hand, a steep increase in swim bladder barotrauma was detected with decreasing distance to the pile driving source: no swim bladders were ruptured at 1700 m nor at the control treatments, 20 % were ruptured at 1400 m distance, 40 % at 400 m distance and up to 90 % of the swim bladders were ruptured at 75 m distance. Although most fishes in the cages in the direct vicinity of the piling source (50-100 m distance) did survive this short term experiment, they all showed many internal bleedings and a high degree of abnormal swimming behavior, indicating they would probably not survive on the longer term. However, these immediate detrimental effects seem to be only a local effect, close to the high impulsive sound source, as swim bladder injuries rapidly decreased with increasing distance from the pile driving source. Based on these results, a sound threshold of 165 dB re 1µPa²s for SELss and 185 dB re 1µPa for SPLz-p may be suggested as precautionary approach to avoid internal injuries.

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