Marine and freshwater sounds impact invertebrate behaviour and physiology: A meta-analysis

Supplementary file: Supplemental Tables S1–S7 and Supplemental Figures S1–S5

Journal name: *Global Change Biology*

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Table S1. Peer-reviewed studies included in this meta-analysis, and the associated number of data points derived from each study, addressing invertebrate a) behaviour and b) physiology. Five studies addressing both behavioural and physiological responses are listed in both tables (Celi et al., 2013; Jolivet et al., 2016; Kunc et al., 2014; Peng et al., 2016; Wale et al., 2019).

a) Behaviour

Authors	Study title	Data points
Anderson et al. 2021	Response of fish and invertebrate larvae to backreef sounds at varying distances: implications for habitat restoration	20
Andriguetto-Filho et al. 2005	Evaluating the impact of seismic prospecting on artisanal shrimp fisheries	2
Celi et al. 2013	Physiological and agonistic behavioural response of *Procambarus clarkii* to an acoustic stimulus	8
Charifi et al. 2018	Noise pollution limits metal bioaccumulation and growth rate in a filter feeder, the Pacific oyster *Magallana gigas*	6
Filiciotto et al. 2018	Are semi-terrestrial crabs threatened by human noise? Assessment of behavioural and biochemical responses of *Neohelice granulata* (Brachyura, Varunidae) in tank	2
Hubert et al. 2018	Effects of broadband sound exposure on the interaction between foraging crab and shrimp – A field study	4
Hubert et al. 2022	Responsiveness and habituation to repeated sound exposures and pulse trains in blue mussels	22
Hudson et al. 2022	Potential impacts from simulated vessel noise and sonar on commercially important invertebrates	8
Hughes et al. 2014	Predatory fish sounds can alter crab foraging behaviour and influence bivalve abundance	4
Jolivet et al. 2016	Validation of trophic and anthropic underwater noise as settlement trigger in blue mussels	1
Kunc et al. 2014	Anthropogenic noise affects behavior across sensory modalities	2
Lagardère 1982	Effects of noise on growth and reproduction of *Crangon crangon* in rearing tanks	12

Lecchini et al. 2018	Boat noise prevents soundscape-based habitat selection by coral planulae	30
Lillis et al. 2013	Oyster larvae settle in response to habitat-associated underwater sounds	4
Lillis et al. 2015	Soundscape manipulation enhances larval recruitment of a reef-building mollusk	8
Peng et al. 2016	Effects of anthropogenic sound on digging behavior, metabolism, Ca 2+/Mg2+ ATPase activity, and metabolism-related gene expression of the bivalve *Sinonovacula constricta*	6
Roberts & Laidre 2019	Finding a home in the noise: cross-modal impact of anthropogenic vibration on animal search behaviour	1
Stanley et al. 2014	Fouling in your own nest: vessel noise increases biofouling	18
Stocks et al. 2012	Response of marine invertebrate larvae to natural and anthropogenic sound: a pilot study	10
Tidau & Briffa 2019	Distracted decision makers: ship noise and predation risk change shell choice in hermit crabs	2
Wale et al. 2013b	Noise negatively affects foraging and antipredator behaviour in shore crabs	3
Wale et al. 2019	From DNA to ecological performance: effects of anthropogenic noise on a reef-building mussel	2

b) Physiology

Authors	Study title	Data points
Carter et al. 2020	Ship noise inhibits colour change, camouflage, and anti-predator behaviour in shore crabs	2
Celi et al. 2013	Physiological and agonistic behavioural response of *Procambarus clarkii* to an acoustic stimulus	10
Celi et al. 2015	Shipping noise affecting immune responses of European spiny lobster (*Palinurus elephas*)	5

Day et al. 2016	Seismic air gun exposure during early-stage embryonic development does not negatively affect spiny lobster *Jasus edwardsii* larvae (Decapoda:Palinuridae)	15
Day et al. 2017	Exposure to seismic air gun signals causes physiological harm and alters behavior in the scallop *Pecten fumatus*	38
Day et al. 2019	Seismic air guns damage rock lobster mechanosensory organs and impair righting reflex	44
Filiciotto et al. 2014	Behavioural and biochemical stress responses of *Palinurus elephas* after exposure to boat noise pollution in tank	16
Filiciotto et al. 2016	Underwater noise from boats: measurement of its influence on the behaviour and biochemistry of the common prawn (*Palaemon serratus*, Pennant 1777)	6
Fitzgibbon et al. 2017	The impact of seismic air gun exposure on the haemolymph physiology and nutritional condition of spiny lobster, *Jasus edwardsii*	223
Hudson et al. 2022	Potential impacts from simulated vessel noise and sonar on commercially important invertebrates	32
Jolivet et al. 2016	Validation of trophic and anthropic underwater noise as settlement trigger in blue mussels	4
Kunc et al. 2014	Anthropogenic noise affects behavior across sensory modalities	1
McCauley et al. 2017	Widely used marine seismic survey air gun operations negatively impact zooplankton	6
Nedelec et al. 2014	Anthropogenic noise playback impairs embryonic development and increases mortality in a marine invertebrate	2
Pearson et al. 1994	Effects of seismic energy release on the survival and development of zoeal larvae of Dungeness Crab (*Cancer magister*)	15
Peng et al. 2016	Effects of anthropogenic sound on digging behavior, metabolism, Ca 2+/Mg2+ ATPase activity, and metabolism-related gene expression of the bivalve *Sinonovacula constricta*	28
Przeslawski et al. 2018	Multiple field-based methods to assess the potential impacts of seismic surveys on scallops	18

Regnault & Lagardère 2018	Effects of ambient noise on the metabolic level of *Crangon crangon* (Decapoda, Natantia)	18
Ren et al. 2021	Music stimulus has a positive effect on survival and development of the larvae in swimming crab *Portunus trituberculatus*	45
Shi et al. 2019	Anthropogenic noise aggravates the toxicity of cadmium on some physiological characteristics of the blood clam *Tegillarca granosa*	28
Solé et al. 2016	Evidence of cnidarians sensitivity to sound after exposure to low frequency underwater sources	2
Solé et al. 2017	Offshore exposure experiments on cuttlefish indicate received sound pressure and particle motion levels associated with acoustic trauma	1
Solé et al. 2018	A critical period of susceptibility to sound in the sensory cells of cephalopod hatchlings	12
Solé et al. 2019	A proteomic analysis of the statocyst endolymph in common cuttlefish (*Sepia officinalis*): an assessment of acoustic trauma after exposure to sound	2
Solé et al. 2021	An acoustic treatment to mitigate the effects of the Apple Snail on agriculture and natural ecosystems	1
Tu et al. 2021	Transcriptome analysis of the central nervous system of sea slug (*Onchidium reevesii*) exposed to low-frequency noise	30
Vazzana et al. 2020	Underwater high frequency noise: biological responses in sea urchin *Arbacia lixula* (Linnaeus, 1758)	8
Wale et al. 2013a	Size-dependent physiological responses of shore crabs to single and repeated playback of ship noise	8
Wale et al. 2019	From DNA to ecological performance: effects of anthropogenic noise on a reef-building mussel	8
Zhao et al. 2021	Mussel byssal attachment weakened by anthropogenic noise	32

Table S2. The broader sound source categories used in this meta-analysis, as well as the specific sound sources included within these, the number of studies, and number of data points. The categories are divided into the two main response types: a) behaviour and b) physiology.

a) Behaviour

Sound category	Sound source	Studies	Data
Anthropogenic noise	Pile driving	1	1
	Seismic surveys	2	6
	Shipping noise	10	49
	Tank noise	1	12
Environmental sounds	Animal bioacoustics	1	4
	Environmental	5	61
Synthetic sounds	Linear sweep	1	8
	Tone	3	28
	White noise	2	6

b) Physiology

Sound category	Sound source	Studies	Data
Anthropogenic noise	Pile driving	2	60
	Seismic surveys	8	375
	Shipping noise	10	68
	Tank noise	1	18
Music	Music	1	45
Synthetic sounds	Linear sweep	2	18
	Tone	6	48
	White noise	1	28

Table S3. The specific responses and number of data points within each meta-analytic multivariate mixed-effects model variable. The variables are divided into the two main response types: a) behaviour and b) physiology.

a) Behaviour

Model variable	Responses	Data
Bioacoustics	Acoustic emissions (i.e., crab sound production)	2
Defence	Bivalve gape (i.e., amount, cadmium concentration as bivalve gape proxy, fraction of bivalves open, time open), digging depth (i.e., of clams), fights (i.e., with other crayfish), hiding time, raised arms (i.e., frequency), righting time, shell decision time (i.e., accept/reject hermit crab shells), sheltering, tail flips	49
Foraging	Foraging (i.e., clams consumed), foraging time, monthly consumption, number foraging, number near food source	21
Movement	Activity level (i.e., movement into and out of circles, velocity), chemical cue attraction (i.e., number of hermit crabs attracted to a newly available shell), encounters (i.e., with other crayfish), number moving, abundance, time swimming	22
Recruitment	Recruitment (i.e., density/direct counts, number of individuals per settlement panel, number of larvae per collector, proportion of larvae settled)	81

b) Physiology

Model variable	Responses	Data
Biochemistry	ATP content, calorimetry, clearance rate (i.e., of food), enzyme activity, excretion (i.e., ammonia, O:N ratio), heat shock proteins, hemocyte count, hemolymph chemistry (e.g., Cl, K, Na), hemolymph glucose, hemolymph refractive index, hemolymph pH, hemolymph protein, hemolysis, hepatopancreas index, reactive oxygen species, respiration rate (i.e., oxygen), statocyst protein	430
Defence	Colour changes (i.e., amount, number)	3
Development	Development failure (i.e., failed eggs, unhatched eggs), development success (i.e., hatched larvae), development time, percent metamorphosis	28
Genetics	DNA damage, gene expression	62

Morphology	Body mass, body size (i.e., length, width), byssal thread size, byssal thread strength, condition (i.e., of reproductive organs), hair cell damage (i.e., number of intact hair cells, percent mean damaged hair cells)	107
Survival	Survival rate (i.e., cumulative, to stage III or IV larvae, ratio of dead/total zooplankton)	30

Table S4. Structure of the meta-analytic multivariate mixed-effects response models for each behavioural and physiological response type and sound source category, including the Box Cox transformation value, fixed effect, random effect (data point ID or data point ID nested within study), and exclusion of response categories (due to the exclusion condition of studies with less than three data points).

Response type	Sound	Transform	Fixed	Random	Exclusion
Behaviour	Anthropogenic	0.700	Response type	Study / ID	-
	Environmental	0.869	Response type	Study / ID	-
	Synthetic	0.636	Response type	Study / ID	Bioacoustics
Physiology	Anthropogenic	1.600	Response type	Study / ID	-
	Music	0.465	Response type	ID	-
	Synthetic	1.400	Response type	Study / ID	-

Table S5. Meta-analytic multivariate mixed-effect response model outputs quantifying the impacts of each sound source category on aquatic invertebrate a) behavioural and b) physiological responses. Behavioural models included response as a fixed effect and data point ID nested within study as a random effect. The number of studies included in each behavioural model were 13 for anthropogenic, 6 for environmental, and 5 for synthetic. For physiological models, anthropogenic noise and synthetic sound included response as a fixed effect and data point ID nested within study as a random effect, and music included response as a fixed effect and data point ID as a random effect. The number of studies included in each physiological model were 20 for anthropogenic, 1 for music, and 9 for synthetic. Standard error is represented as SE, confidence intervals include the lower (Low CI) and upper (Up CI) bounds, and significant p-values are bolded (p < 0.05).

a) Behaviour

Sound	Response	Estimate	SE	z-value	p-value	Low CI	Up CI
Anthropogenic	Defence	–0.60	0.22	–2.72	**0.007**	–1.03	–0.17
	Foraging	–0.08	0.37	0.20	0.841	–0.66	0.81
	Movement	–0.44	0.23	–1.95	0.051	–0.88	0.00
	Recruitment	0.50	0.38	1.30	0.192	–0.25	1.24
Environmental	Foraging	–0.07	0.25	–0.27	0.789	–0.55	0.42
	Movement	0.09	0.14	0.63	0.529	–0.18	0.36
	Recruitment	0.10	0.09	1.19	0.236	–0.07	0.27
Synthetic	Defence	–0.37	0.17	–2.15	**0.032**	–0.72	–0.03
	Foraging	–0.07	0.35	–0.21	0.831	-0.76	0.61
	Movement	–0.23	0.45	–0.51	0.598	–1.10	0.65

b) Physiology

Sound	Response	Estimate	SE	z-value	p-value	Low CI	Up CI
Anthropogenic	Biochemistry	–2.06	0.61	–3.38	**0.001**	–3.26	–0.87
	Defence	–2.04	1.92	–1.06	0.287	–5.79	1.72
	Development	–1.45	0.93	–1.55	0.122	–3.28	0.39
	Genetics	–4.43	0.74	–5.99	**<0.0001**	–5.88	–2.98
	Morphology	–1.63	0.72	–2.28	**0.023**	–3.04	–0.23
	Survival	–1.31	1.16	–1.14	0.256	–3.58	0.95
Music	Biochemistry	0.45	0.20	2.25	**0.025**	0.06	0.84
	Development	0.16	0.18	0.85	0.395	–0.20	0.52
	Survival	0.33	0.20	0.68	0.094	–0.06	0.71
Synthetic	Biochemistry	–1.87	1.23	–1.52	0.128	–4.28	0.54
	Genetics	–4.72	1.43	–3.29	**0.001**	–7.53	–1.91
	Morphology	–5.91	1.79	–3.30	**0.001**	–9.42	–2.40

Table S6. Structure of the meta-analytic multivariate mixed-effects taxa models for each behavioural and physiological response type and sound source category, including the Box Cox transformation value, fixed effect, random effect (data point ID or data point ID nested within study), and exclusion of response categories (due to the exclusion condition of studies with less than three data points).

Response type	Sound	Transform	Fixed	Random	Exclusion
Behaviour	Anthropogenic	0.700	Phylum	Study / ID	Annelida, Echinodermata
	Environmental	0.869	Phylum	Study / ID	Bryozoa, Echinodermata
	Synthetic	0.737	Phylum	Study / ID	-
Physiology	Anthropogenic	1.600	Phylum	Study / ID	Zooplankton
	Music	0.465	-	ID	-
	Synthetic	2.400	Phylum	Study / ID	Cnidaria

Table S7. Meta-analytic multivariate mixed-effect response taxa model outputs quantifying the impacts of each sound source category on aquatic invertebrate a) behavioural and b) physiological responses. Behavioural models included response as a fixed effect and data point ID nested within study as a random effect. The number of studies included in each behavioural model were 13 for anthropogenic, 6 for environmental, and 5 for synthetic. For physiological models, anthropogenic noise and synthetic sound included response as a fixed effect and data point ID nested within study as a random effect, music included response as a fixed effect and data point ID as a random effect, and natural sounds just included data point ID as a random effect. The number of studies included in each physiological model were 20 for anthropogenic, 1 for music, and 8 for synthetic. Standard error is represented as SE, confidence intervals include the lower (Low CI) and upper (Up CI) bounds, and significant p-values are bolded ($p < 0.05$).

a) Behaviour

Sound	Response	Estimate	SE	z-value	p-value	Low CI	Up CI
Anthropogenic	Arthropoda	–0.30	0.25	–1.23	0.218	–0.79	0.18
	Bryozoa	–0.18	0.53	–0.33	0.738	–1.21	0.86
	Cnidaria	–0.52	0.65	–0.79	0.429	–1.79	0.76
	Mollusca	–0.11	0.29	–0.39	0.698	–0.68	0.46
Environmental	Arthropoda	0.02	0.06	0.33	0.745	–0.11	0.15
	Cnidaria	0.04	0.11	0.37	0.708	–0.17	0.26
	Mollusca	0.10	0.05	1.94	0.053	–0.00	0.20
Synthetic	Arthropoda	–0.32	0.26	–1.25	0.211	–0.83	0.18
	Mollusca	–0.48	0.22	–2.17	**0.030**	–0.90	–0.05

b) Physiology

Sound	Response	Estimate	SE	z-value	p-value	Low CI	Up CI
Anthropogenic	Arthropoda	–2.00	0.72	–2.79	**0.005**	–3.41	–0.60
	Mollusca	–2.08	0.90	–2.31	**0.021**	–3.85	–0.31
Music	Arthropoda	0.30	0.11	2.72	**0.007**	0.08	0.52
Synthetic	Arthropoda	–6.02	2.66	–2.26	**0.024**	–11.23	–0.80
	Echinodermata	–4.68	2.82	–1.66	0.096	–10.20	0.84
	Mollusca	–4.96	0.93	–5.35	**<0.0001**	–6.78	–3.14

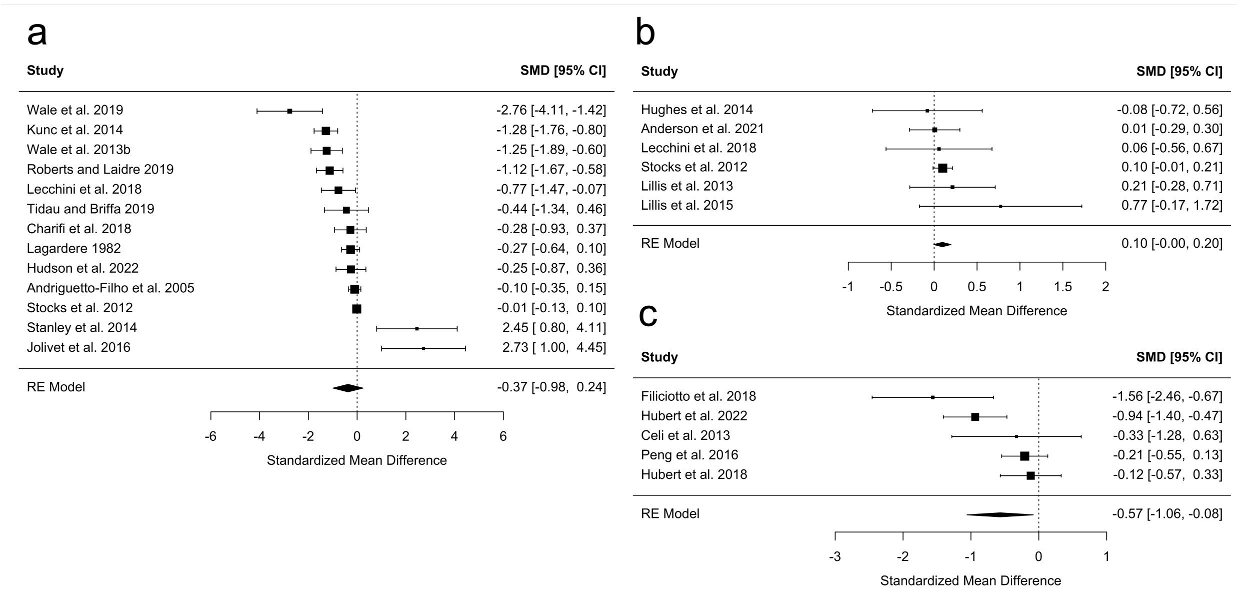

Figure S1. Forest plots showing how various types of aquatic sound affected invertebrate behaviour. Studies were divided into the following categories based on sound source: a) anthropogenic noise, b) environmental sounds, and c) synthetic sounds. Authors and publication year are listed with each effect size and 95% confidence intervals. The black squares are the effect sizes, which are scaled based on their weight in the analysis (larger studies have larger points). The diamond at the bottom of each sound source plot illustrates the summary effect (weighted average of individual study effect sizes).

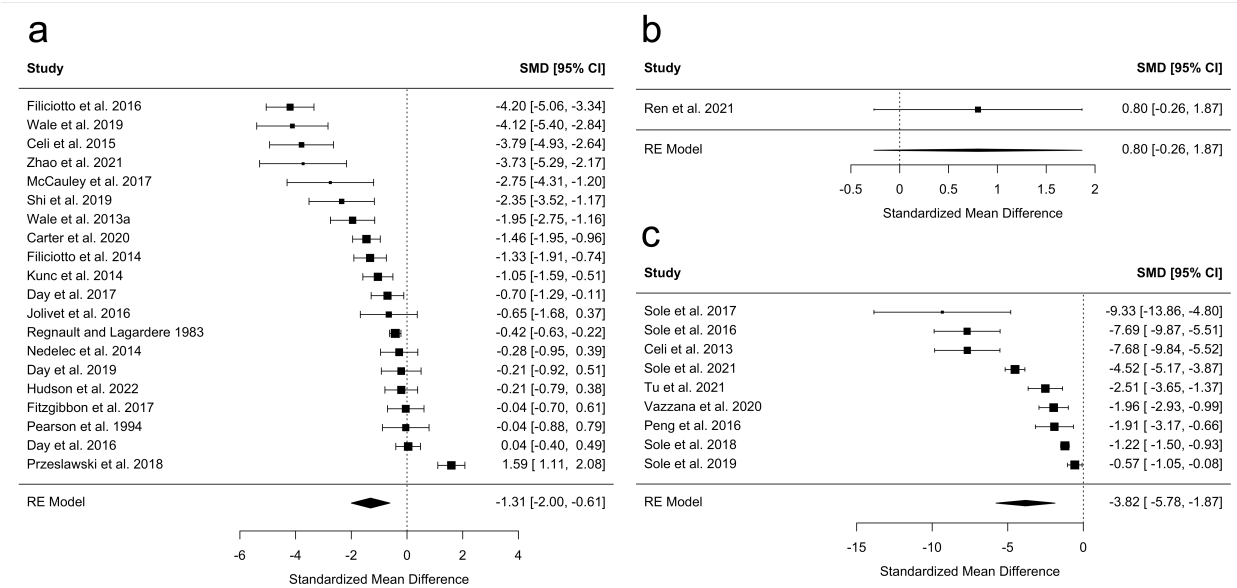

Figure S2. Forest plots showing how various types of aquatic sound affected invertebrate physiology. Studies were divided into the following categories based on sound source: a) anthropogenic noise, b) music, and c) synthetic sounds. Authors and publication year are listed with each effect size and 95% confidence intervals. The black squares are the effect sizes, which are scaled based on their weight in the analysis (larger studies have larger points). The diamond at the bottom of each sound source plot illustrates the summary effect (weighted average of individual study effect sizes).

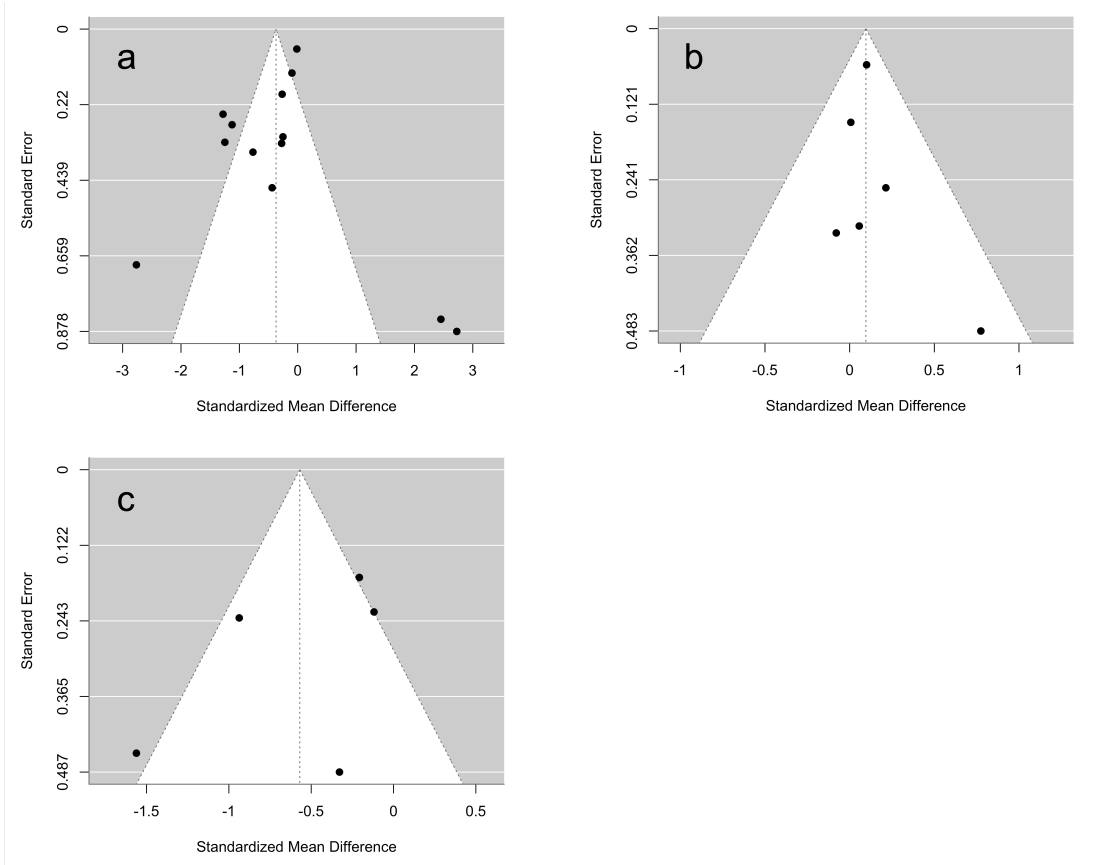

Figure S3. Funnel plots examining the presence of publication bias within each sound source category affecting aquatic invertebrate behavioural responses, including a) anthropogenic noise, b) environmental sounds, and c) synthetic sounds.

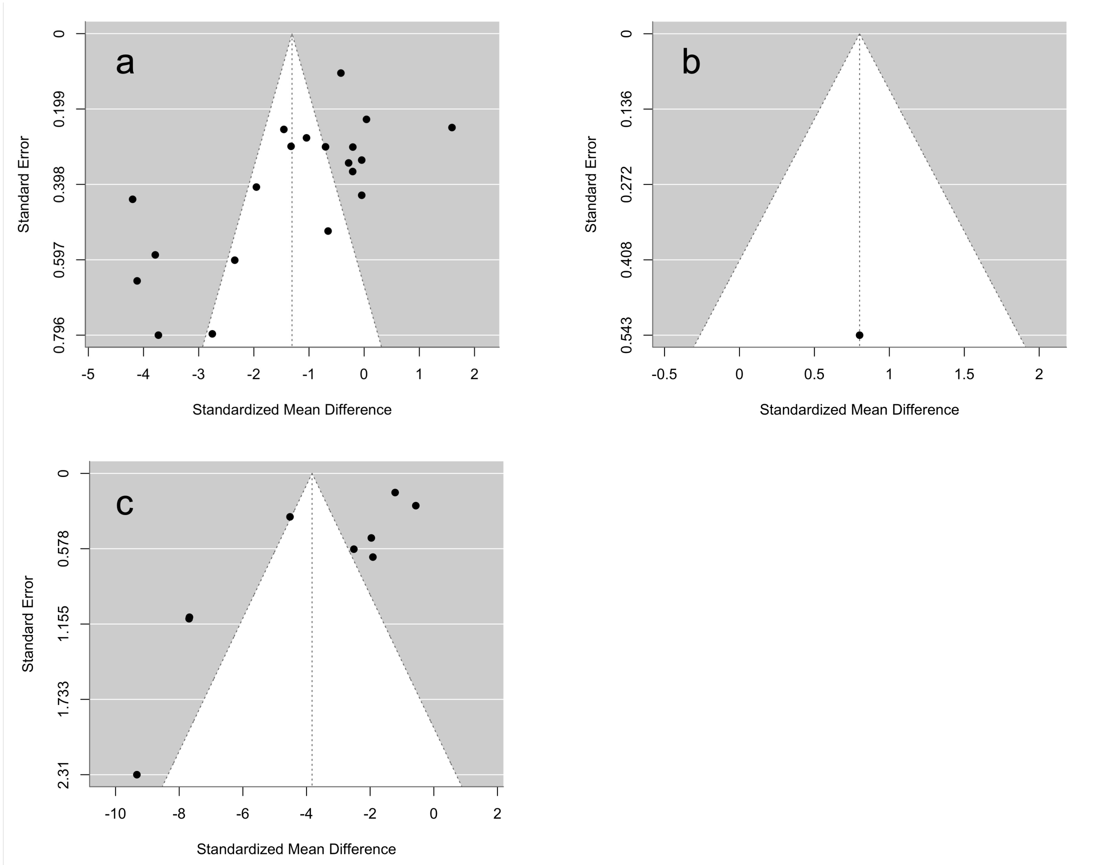

Figure S4. Funnel plots examining the presence of publication bias within each sound source category affecting aquatic invertebrate physiological responses, including a) anthropogenic noise, b) music, and c) environmental sounds.

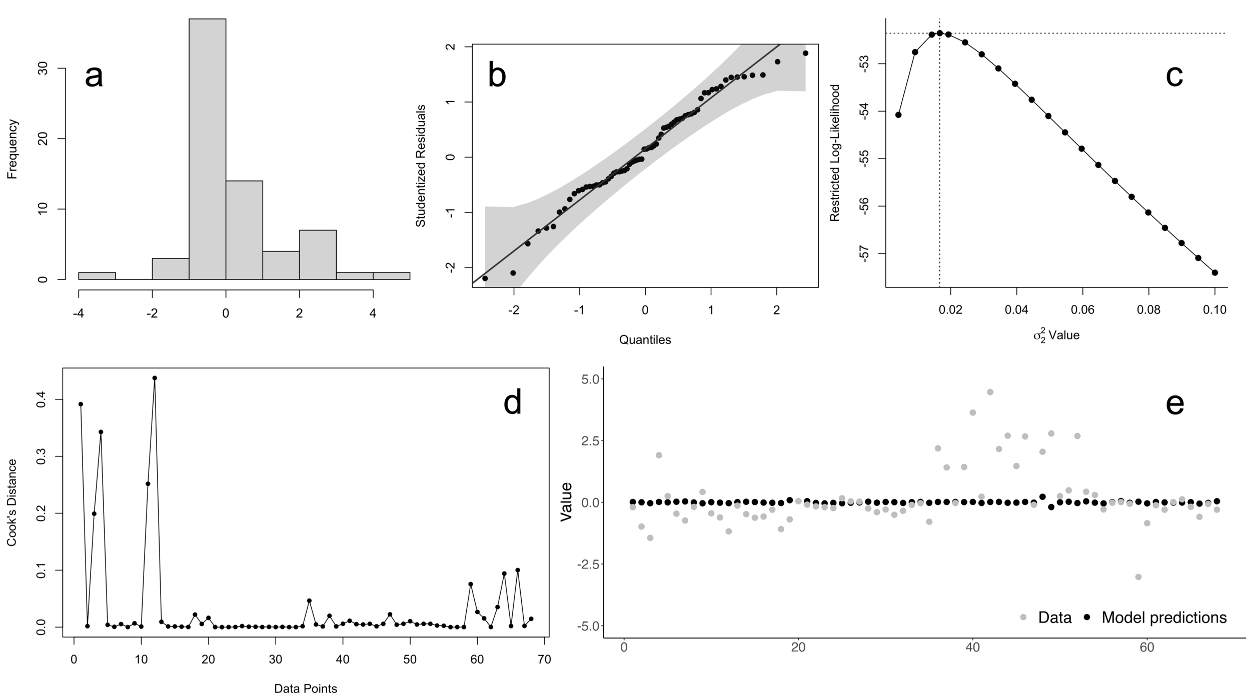

Figure S5. An example of the statistical test visualizations used to assess the validity of each meta-analytic multivariate mixed-effects model in this meta-analysis, using the effects of anthropogenic sounds on behavioural response categories model. a) A transform was identified using the Box Cox method and the transformed histogram visually examined. b) Model studentized residuals were examined for normality using a quantile-quantile plot. c) The variance components of the model residuals were examined using a profile likelihood plot. d) The plot of Cook's distance values aided identification of influential data points to be further examined (along with DFBETAS and hat values not shown here). e) A comparison of our data (grey) with the model predictions (black) to visualize how well the model predicted our data (followed by a t-test).