Electronic Supplemental Materials for "Blue whales respond to simulated mid-frequency sonar"

Authors:

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Author contributions:

Experimental design (BLS, JC, PLT), Visual observations and geospatial data (AD, CK, EF), Tagging operations (JAG, JC, ASF, EF, GS), Sound exposure operations (BLS, DM, CK), Tag data analysis (JAG, SD, MFM), Statistical analysis (ELH, SLD, JAG), Manuscript preparation (JAG, BLS, ELH), Manuscript revision (JAG, BLS, ASF, ELH, JC, PLT).

Fine-scale movement for select CEE examples (Figure 1A, B).

The data shown in Figure 1 is summarized to represent the nature of our broad scale analysis, where parameters were assessed on a dive-by-dive basis. Here we provide additional details on the fine-scale kinematics for two CEEs shown in Figure 1b and Figure 1c, including speed (Figure S1, S2) and body orientation relative to the sound source (Figure S3, S4, S5) as visualized in TrackPlot. An animation of the whale's estimated trajectory during the CEE (Figure 1B) is provided by the supplemental movie (bw10_244c).

The CEE in Figure S1 show data from a blue whale in a non-feeding behavioral state being exposed to mid-frequency simulated military sonar (MFA). The onset of sound exposure occurs during a mid-water dive where the whale was at a depth of approximately 30 m. The ascent phase following sound exposure was unusually prolonged and contained multiple undulations that do not normally occur during mid-water traveling dives (Figure S1 b,c). In addition, there was a marked increase in swimming speed (> 4 m s^{-1}) during the ascent phase of the initial exposure dive. We note that the acoustic record was clipped at this speed maximum (~16:49), so the speed estimated at that time is likely an underestimate and the whale's true speed could be as high as 5 m s^{-1}. Such speeds are consistent with field observations of flight speeds for blue whales when threatened by killer whales [1], although this blue whale exhibited a gradual decrease in speed for the remainder of the exposure period and therefore does not constitute a true flight response.

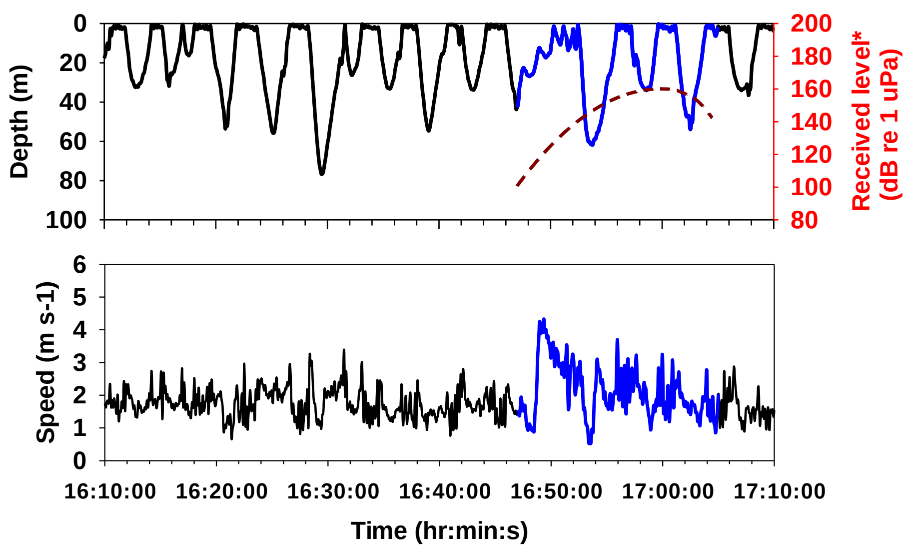

Figure S1. Fine-scale movement for the CEE shown in Figure 1C. *A blue whale in a non-feeding behavioral state was exposed to simulated mid-frequency military sonar. Dive profile* *(black trace) and received sound levels (red circles and dashed line represent pings and the estimated received level via a quadratic spline).*

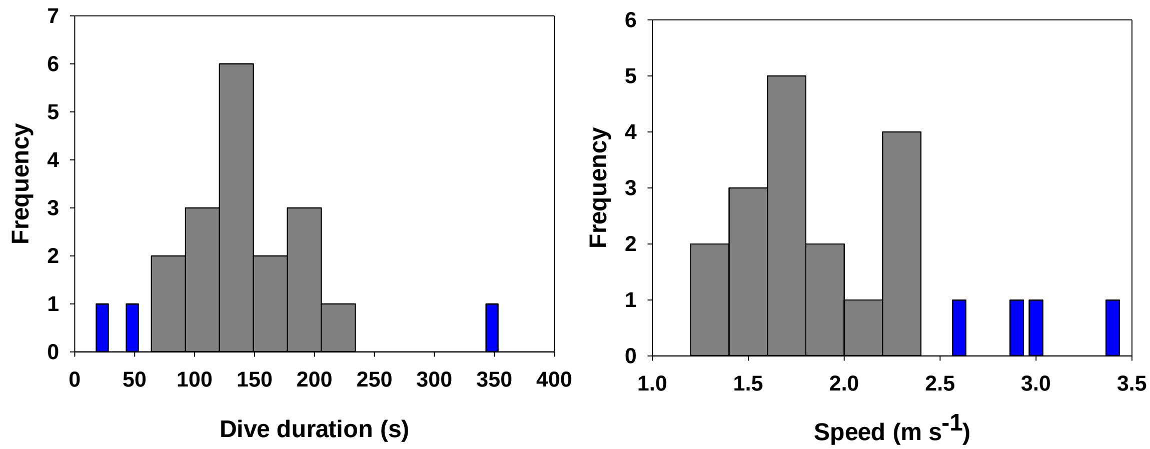

Figure S2. Histograms for two primary response parameters before and during sound exposure for the CEE shown in Figure 1c. *The mean values of each response parameter during all dives before exposure (gray) and the first four dives during exposure (blue).*

The CEE in Figures S3-S4 show data from a blue whale in a deep feeding mode (A) being exposed to pseudo-random noise (PRN). The onset of sound exposure occurs when the whale was at a depth of approximately 150 m (Figure S3B, S3B). During the ascent phase of the dive following sound exposure the whale appears to localize and orient towards the sound source (Figure S3C, S4C). The whale then turns away from the sound source during the first surface series (a sequence of breaths that follows a deep dive) following sound exposure (Figure S3D, S4D). The whale establishes a relatively steady heading over the next series of non-foraging dives and gradually increases speed (Figure S3E, S4E). The whale returns to a deep feeding behavioral state approximately 1 hour after the start of sound exposure. We have also provided an animation "bw10_244cObliqueWaudio" of the initial phase of this CEE. The symbols in the animation follow those in Figures S3-S4. Speed is 20x actual.

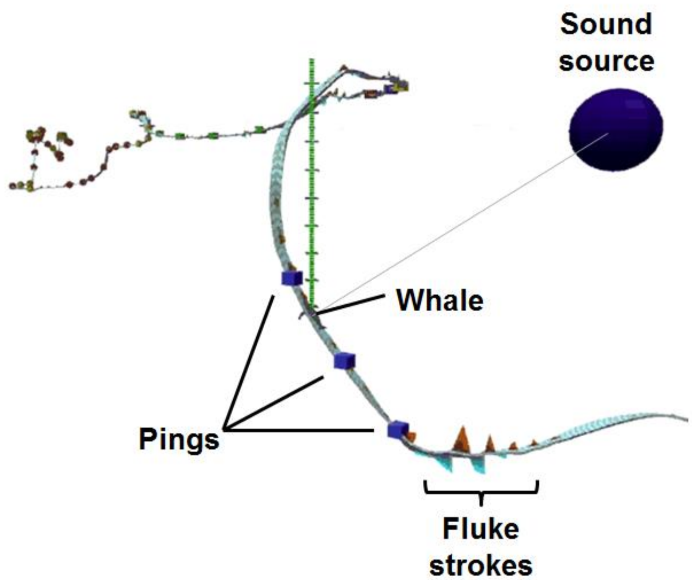

Figure S3. Explanation of TrackPlot symbols. *The estimated trajectory of the tagged whale is represented by a ribbon. The whale's fluking strokes are represented by triangles that erupt above and below the ribbon to indicate upstrokes and down-strokes, respectively. The timing of each ping of sound, as detected by the hydrophone, is represented by a cube along the ribbon. The color of each cube reflects the magnitude of the received sound level, where hotter colors indicate higher received levels. The green line is orthogonal to the sea surface (large hatched marks denote 10 m depth intervals).*

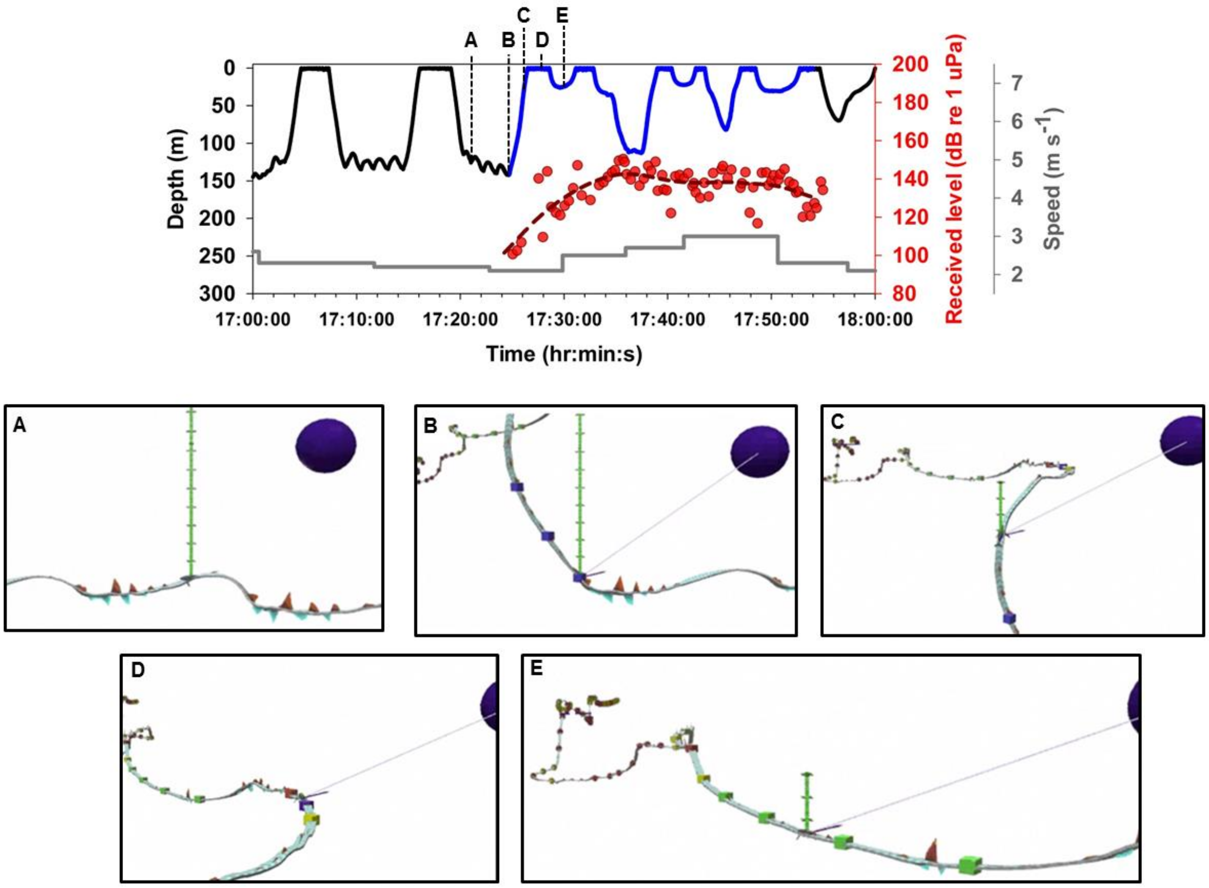

Figure S4. Oblique view of the tagged whale's behavior during the exposure experiment (Figure 1B). *A blue whale in a deep feeding behavioral state was exposed to simulated pseudo-random noise. (**A**) Undulations in the dive profile indicate lunge feeding at depth prior to sound exposure. (**B**) Time of the first received ping. (**C**) Whale appears to localize and orient towards the sound source. (**D**) The whale changes direction during the first surface series after sound exposure. (**E**) The whale maintains roughly the same heading at the end of the first surface series.*

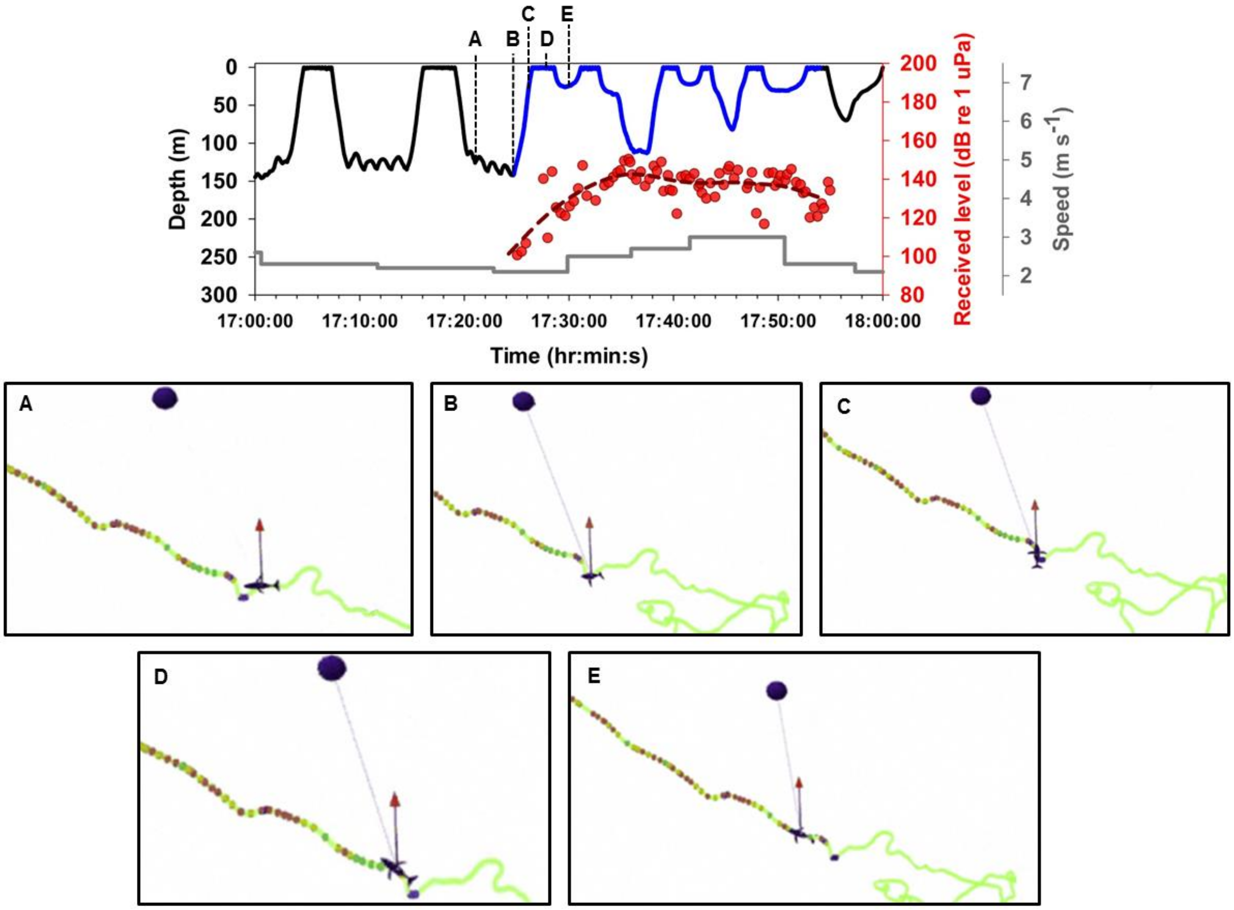

Figure S5. Aerial view of the tagged whale's behavior during the exposure experiment (Figure 1B). *Frames (**A-E**) represent the same stages of the CEE as shown in Figure S4.*

Consumption loss estimate for behavioral response shown in figure 1B (also figure S4-5).

Rorqual whales (Balaenopteridae) are obligate lunge feeders that engulf dense aggregations of prey in discrete mouthfuls [2]. The amount of prey-laden water that a rorqual processes in a single foraging dive is the product of lunge frequency [3] and engulfment capacity [4] and this parameter can be generated over an entire foraging bout [5, 6]. We invoked this methodology to determine the changes in feeding rate over the course of the CEE for the tagged blue whale shown in figure 1b (stimuli: PRN). Before the CEE, the blue whale was continuously foraging at a rate of 4.2 lunges per dive. For an average krill density of 0.5 kg m^{-3} and a mean blue whale engulfment capacity of 110 m^3 [7], the tagged blue whale acquired 1,375 krill in 72 min prior to the onset of sound exposure, thus yielding an overall feeding rate of 19 kg of krill per minute. The tagged blue whale stopped feeding at the onset of sound exposure for a total of 62 minutes, suggesting that this behavioral response in the form cessation of feeding resulted in an energetic loss of 1,200 krill. The magnitude of this consumption loss is approximately commensurate with a blue whale's daily energetic demand [7]. Therefore, this example suggests that exposure of mid-frequency anthropogenic sound could have major effects on blue whale foraging ecology.

Detailed results from statistical analyses

Paired PCA-GAMM Results

Our paired PCA-GAMM analyses revealed significant differences related to sound exposure. The primary eigenvector of all three parameter groupings had a significant effect with respect to sound exposure (Dive metrics, p=0.045; r^2 adj = 0.16; orientation metrics, p = 0.019; r^2 adj = 0.03; horizontal metrics, p<0.005; r^2 adj = 0.07), with dive metrics specifically showing a three-way interaction effect among treatment status, treatment dive (descent, ascent, or bottom phase), and behavioral state. Although responses clearly varied among individuals (Figure 1), some of the variability was explained by behavioral state and sound type (Figure 2, Table S1).

Dive Axis 1 – Before/During/After model (r^2 adj.=0.14, n=430)	**Estimate**	**t statistic**	**p-value**
(Intercept)	1.11522	0.908	0.3646
Treatment.status	0.14671	1.561	0.1193
Treatment.dive	**0.01645**	**0.110**	**0.9125**
Bstate.PB	-1.11144	-1.769	0.0776
Treatment.status:Treatment.dive:Bstate.PB	**0.20095**	**2.088**	**0.0374**
	Deg Free	**F statistic**	**p-value**
s(MaxRL)	4.343e-08	0.071	0.790
s(MinRL)	1.427e-08	0.000	0.996
s(AvgRL)	2.831e-08	0.025	0.875
s(X.Pings)	**9.629e-01**	**18.444**	**2.17e-05**

Dive Axis 1 - During model (r^2=0.38, n=88)	**Estimate**	**t statistic**	**p-value**
(Intercept)	2.8532	1.35	0.1806
Treatment.dive	-0.2779	-1.079	0.2836
Treatment.type	-1.0218	-0.779	0.4379
Bstate.PB	**-1.6198**	**-2.032**	**0.0454**
Treatment.dive:Treatment.type:Bstate.PB	**0.2217**	**2.172**	**0.0327**
	Est Deg Free	**F statistic**	**p-value**
s(MaxRL)	**2.1683**	**9.583**	**0.000129**
s(MinRL)	**0.81**	**4.501**	**0.036852**
s(AvgRL)	0.8032	3.499	0.064916
S(X.Pings)	**2.1683**	**9.583**	**0.000129**

Orientation Axis 1 - Before/During/After model (r^2= 0.04, n=430)	**Estimate**	**t statistic**	**p-value**
(Intercept)	0.8153	0.51	0.6104
Treatment.status	**-0.20616**	**-2.354**	**0.0191**
Treatment.dive	-0.14956	-1.073	0.2838
Bstate.PB	-0.02277	-0.03	0.9763
Boats.cat	-0.97714	-0.58	0.5624
Treatment.status:Treatment.dive:Bstate.PB	-0.04193	-0.474	0.6355
	Est Deg Free	**F statistic**	**p-value**

s(MaxRL)	3.93E-08	0.188	0.6648
s(MinRL)	1.35E-08	0.107	0.7434
s(AvgRL)	3.54E-08	0.167	0.683
S(X.Pings)	**8.38E-01**	**6.534**	**0.0109**

Orientation Axis 1 - During model (r^2=-0.01, n=84)	**Estimate**	**t statistic**	**p-value**
(Intercept)	1.1724	0.441	0.661
Treatment.dive	0.1824	0.363	0.718
Treatment.type	1.132	0.966	0.337
Bstate.PB	-0.0718	-0.056	0.955
Boats.cat	-3.3751	-1.309	0.194
Treatment.dive:Treatment.type:Bstate.PB	-0.2612	-1.168	0.246
	Est Deg Free	**F statistic**	**p-value**
s(MaxRL)	1.27E-09	0.013	0.909
s(MinRL)	1.24E-09	0.036	0.85
s(AvgRL)	3.97E-09	0.017	0.896

Orientation Axis 2 - Before/During/After model (r^2=0, n=430)	**Estimate**	**t statistic**	**p-value**
(Intercept)	0.61669	0.786	0.432
Treatment.dive	-0.10039	-1.111	0.267
Treatment.status	-0.02914	-0.512	0.609
Bstate.PB	-0.29209	-0.779	0.436
Boats.cat	-0.26123	-0.316	0.752
Treatment.dive:Treatment.status:Bstate.PB	0.02268	0.444	0.657
	Est Deg Free	**F statistic**	**p-value**
s(MaxRL)	1.43E-08	0.259	0.611
s(MinRL)	5.81E-09	0.049	0.825
s(AvgRL)	1.74E-08	0.232	0.63

Orientation Axis 2 - During model (r^2=0.06, n=87)	**Estimate**	**t statistic**	**p-value**
(Intercept)	0.509635	0.561	0.576

Treatment.dive	0.008127	0.031	0.976
Treatment.type	-0.97422	-1.537	0.128
Bstate.PB	-0.28422	-0.643	0.522
Boats.cat	0.266359	0.277	0.783
Treatment.dive:Treatment.type:Bstate.PB	0.082943	0.79	0.432
	Est Deg Free	**F statistic**	**p-value**
s(MaxRL)	8.50E-10	0.003	0.96
s(MinRL)	6.97E-10	0.061	0.805
s(AvgRL)	1.44E-09	0.001	0.981

Horizontal Metrics Axis 1 - Before/During/After model (r^2=0.07, n=418)	**Estimate**	**t statistic**	**p-value**
(Intercept)	-0.83852	-0.671	0.503
Treatment.status	**0.45282**	**7.427**	**6.46E-13**
Treatment.dive	-0.01493	-0.156	0.876
Bstate.PB	0.29095	0.486	0.627
Boats.cat	-0.07037	-0.053	0.957
Treatment.status:Treatment.dive:Bstate.PB	-0.00307	-0.057	0.955
	Est Deg Free	**F statistic**	**p-value**
s(MaxRL)	8.24E-09	0.506	0.477
s(MinRL)	1.37E-08	0.473	0.492
s(AvgRL)	2.07E-08	0.494	0.483
s(X.Pings)	1.15E-10	0.154	0.695

Horizontal Metrics Axis 1 - During (r^2=0.01, n=87)	**Estimate**	**t statistic**	**p-value**
(Intercept)	-0.16179	-0.069	0.945
Treatment.dive	0.20745	0.444	0.658
Treatment.type	0.05452	0.042	0.967
Bstate.PB	0.53587	0.474	0.637
Boats.cat	-1.29406	-0.57	0.57
	Est Deg Free	**F statistic**	**p-value**
s(MaxRL)	4.14E-09	0.014	0.905

Horizontal Metrics Axis 2 - Before/During/After model (r^2=0.14, n=418)	**Estimate**	**t statistic**	**p-value**
(Intercept)	-1.02561	-1.537	0.1251
Treatment.status	-0.02018	-0.307	0.7587
Treatment.dive	-0.03087	-0.299	0.7651
Bstate.PB	0.55505	1.745	0.0818
Boats.cat	**1.49556**	**2.138**	**0.0331**
Treatment.status:Treatment.dive:Bstate.PB	-0.01152	-0.197	0.8439
	Est Deg Free	**F statistic**	**p-value**
s(MaxRL)	8.22E-09	0.088	0.766
s(MinRL)	9.80E-09	0.414	0.52
s(AvgRL)	2.32E-08	0.208	0.648
s(X.Pings)	9.63E-09	2.05	0.153

Horizontal Metrics Axis 2 - During (r^2=0.31, n=87)	**Estimate**	**t statistic**	**p-value**
(Intercept)	-1.9134	-2.432	0.01721
Treatment.dive	-0.1201	-0.401	0.68941
Treatment.type	0.2938	0.353	0.72522
Bstate.PB	**0.8393**	**2.212**	**0.02977**
Boats.cat	**2.6607**	**3.206**	**0.00192**
	Est Deg Free	**F statistic**	**p-value**
s(MaxRL)	1.86E-09	0.323	0.572

Horizontal Metrics Axis 3 – Before/During/After model (r^2=0.09, n=418)	**Estimate**	**t statistic**	**p-value**
(Intercept)	-0.76605	-0.959	0.338
Treatment.status	0.06668	1.342	0.18
Treatment.dive	-0.04646	-0.597	0.551
Bstate.PB	0.35273	0.923	0.357
Boats.cat	-0.20514	-0.244	0.807
Treatment.status:Treatment.dive:Bstate.PB	0.03869	0.876	0.381
	Est Deg Free	**F statistic**	**p-value**
s(MaxRL)	1.78E-08	0.388	0.534

s(MinRL)	9.83E-09	0.01	0.922
s(AvgRL)	1.51E-08	0.284	0.595
s(X.Pings)	2.28E-07	2.694	0.101

Horizontal Metrics Axis 3 - During (r^2=0.15, n=87)	**Estimate**	**t statistic**	**p-value**
(Intercept)	-0.644	-0.535	0.594
Treatment.dive	0.2534	0.814	0.418
Treatment.type	-1.1845	-1.36	0.177
Bstate.PB	0.4554	0.781	0.437
Boats.cat	0.0453	0.038	0.97
	Est Deg Free	**F statistic**	**p-value**
s(MaxRL)	4.37E-09	0.042	0.839

Table S1. Paired PCA-GAMM Results.

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