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Sound Fields in Two Small Experimental Test Arenas: A Comparison

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Abstract

Lab-based bioacoustics experiments on fish enable control of confounding factors, yet these experiments often use small tanks that are spatially complex in terms of particle motion and sound pressure levels (SPL). One solution is to submerge an arena in water so the influence of the walls on the acoustic environment is greatly reduced. The experiment answered the following: (1) Can the sound pressure homogeneity in small tanks be improved? (2) Can the particle acceleration (PA) levels in small tanks be reduced? (3) Does submerging small tanks allow the sound field to be reliably described by progressive plane waves? The first setup consisted of a rectangular tank surrounded by air (in-air tank) and the second setup was a cylindrical arena submerged in water (submerged arena). Measurements of a 1 s, 125 dB tone at 400–2000 Hz were taken and mapped. The submerged arena possessed less heterogeneity in SPL and lower levels of PA than the in-air tank. The predicted PA (calculated to fulfill research question three) was a better approximation to the submerged arena than the in-air tank. This study demonstrates that the submerged arena gave greater control over the stimulus that a fish experiences in lab-based experiments.

KeywordsTank· Acoustics· Particle acceleration· Sound pressure· Experimental· Methodology.

Introduction

Both laboratory and in situ bioacoustics experiments on fish have benefits and disadvantages. Experiments that are either fully in situ or in a pen have high behavioral and acoustic validity but low experimental control (Slabbekoorn 2016). Conversely, tank experiments lack acoustic validity due to heterogeneous sound pressure levels (SPL) and particle motion, in which both the amplitude and the directional components vary substantially. While experiments in situ may be more favorable in terms of acoustic validity, indoor tank experiments have a much higher degree of experimental control (Akamatsu et al. 2002). This is advantageous for behavioral studies in which external factors, such as water temperature and ambient noise, may compromise the behavior more so in situ than in the lab (Akamatsu et al. 2002; Johnsson and Näslund 2018). However, the effect of confinement in a tank on the behavior of fish has long been a concern for its potential to generate deviations from wild behavior (Hawkins et al. 2015; Hawkins and Popper 2016; Popper and Hawkins 2018).

Small tanks have complex soundscapes owing to their small size, the elasticity of the tank walls, and the large impedance differences between water and air at the tank boundaries (Rogers et al. 2016). For example, consider a rectangular tank made from glass or acrylic which will have five hard surfaces (four sides and a bottom) and the water surface in close proximity to each other. In such circumstances there is a large degree of scattering from all the boundaries. The tank characteristics, particularly the tank size, shape, and the impedance difference, give rise to reverberation, in which the acoustic field cannot be regarded as homogeneous (Akamatsu et al. 2002).

In acoustic experiments, inhomogeneous sound fields mean that the sound level received by a subject vary according to their position within the experimental arena. In the problem we consider, the received SPL and particle motion experienced by a fish would be subject to a high level of uncertainty. For example, the addition of a fish may perturb the sound field to one that differs from that measured in a fish-less tank, e.g. because of scattering from the swim bladder (which would, of course, also happen if the fish were in the field) (Stanton 1989; Diachok 2001; McKelvey and Wilson 2006). Additionally, the complex nature of the sound field makes it challenging to reproduce.

A practical way to improve sound pressure and particle motion fields, while using readily available equipment, is to alter the experimental methodology, exploiting the reduction in acoustic intensity as the wavefront propagates away from the source. This may involve setups in the field (Debusschere et al. 2014) or in a pen (Hubert et al. 2020). However, the use of tanks allows control of environmental factors which would be impossible in the field (Akamatsu et al. 2002; Gray et al. 2016; Currie et al. 2021). To increase the extent to which a tank is homogeneous and isotropic, large impedance differences should be removed. It would be impractical, and for many experimenters prohibitively expensive, to try to improve sound field homogeneity through the use of (very large) anechoic wedges on the arena walls. For the frequencies in question, these wedges would be of ≈1 m in length (Kolaini and Crum 1994), requiring a very large anechoic tank to provide a working space free of the niches provided by wedges in which the fish could be contained (e.g., by a net). Hence, this study tests a more affordable and practical method, exploiting the reduction in acoustic intensity as the wavefront propagates away from the source (rather than its conversion to heat by wedges) to homogenize the sound field. The experiment aimed to answer the following research questions: (1) Can the sound pressure homogeneity in small tanks be improved? (2) Can the particle acceleration (PA) levels in small tanks be reduced? (3) Does submerging small tanks allow the sound field to be reliably described by progressive plane waves?

Methods

Two experimental setups were considered. The first setup consisted of a rectangular tank surrounded by air (in-air tank) and the second setup was a cylindrical arena submerged in water (submerged arena). For both setups, the sound field was mapped and then compared.

Experimental Setup 1: In-Air Tank

Acoustic mapping was carried out in an experimental arena (86 cm length × 30.2 cm height × 30.8 cm depth) situated within a custom-made still water rectangular acrylic tank (300 cm × 30.8 cm × 30.2 cm; 12 mm thickness; 27 cm water depth; mean ± sd temperature 18.8 ± 1.4 °C) in September 2019 at the University of Southampton’s International Centre for Ecohydraulics Research (ICER) facility, UK. The tank was situated on concrete blocks and surrounded by air on all sides (Fig. 1). Two underwater transducers (Electro-Voice UW-30; maximal output 153 dB re 1 μPa at 1 m for 150 Hz, Lubell Labs, Columbus, OH, USA) were suspended centrally, 13.5 cm from the bottom of the tank and 5 cm away from baffles that flanked the experimental arena.

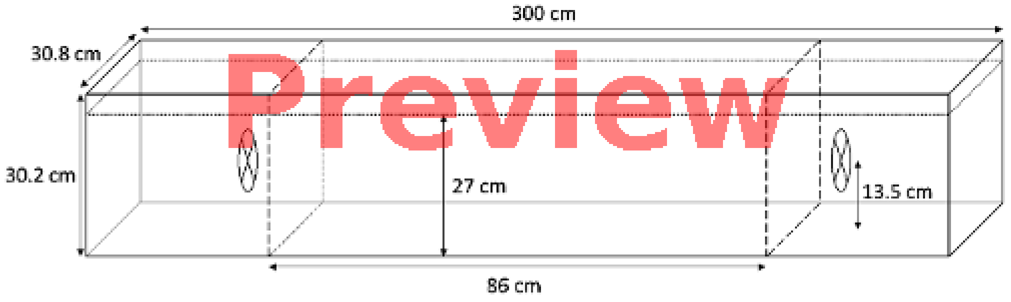

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Fig. 1

The rectangular in-air tank (300 cm length × 30.2 cm height × 30.8 cm depth) and experimental arena (86 cm length) in relation to the water level (dotted line, 27 cm water depth). Two transducers were suspended centrally at either end of the experimental arena and behind an acoustic baffle (dashed line)

Experimental Setup 2: Submerged Arena

Acoustic mapping was carried out in a white medium-density polyethylene cylindrical arena (modified 100 L Round Water Tank; 55.5 cm diameter, 45 cm height; 4 mm thickness; 30 cm water depth; Direct Water Tanks, Retford, Nottinghamshire, UK) in November 2020 at the University of Southampton, UK. The submerged arena was mounted on a bespoke metal frame and suspended in a large tank (8 m length × 8 m width × 5 m depth) (Fig. 2). An underwater transducer (Electro-Voice UW-30) was suspended 70 cm below the arena.

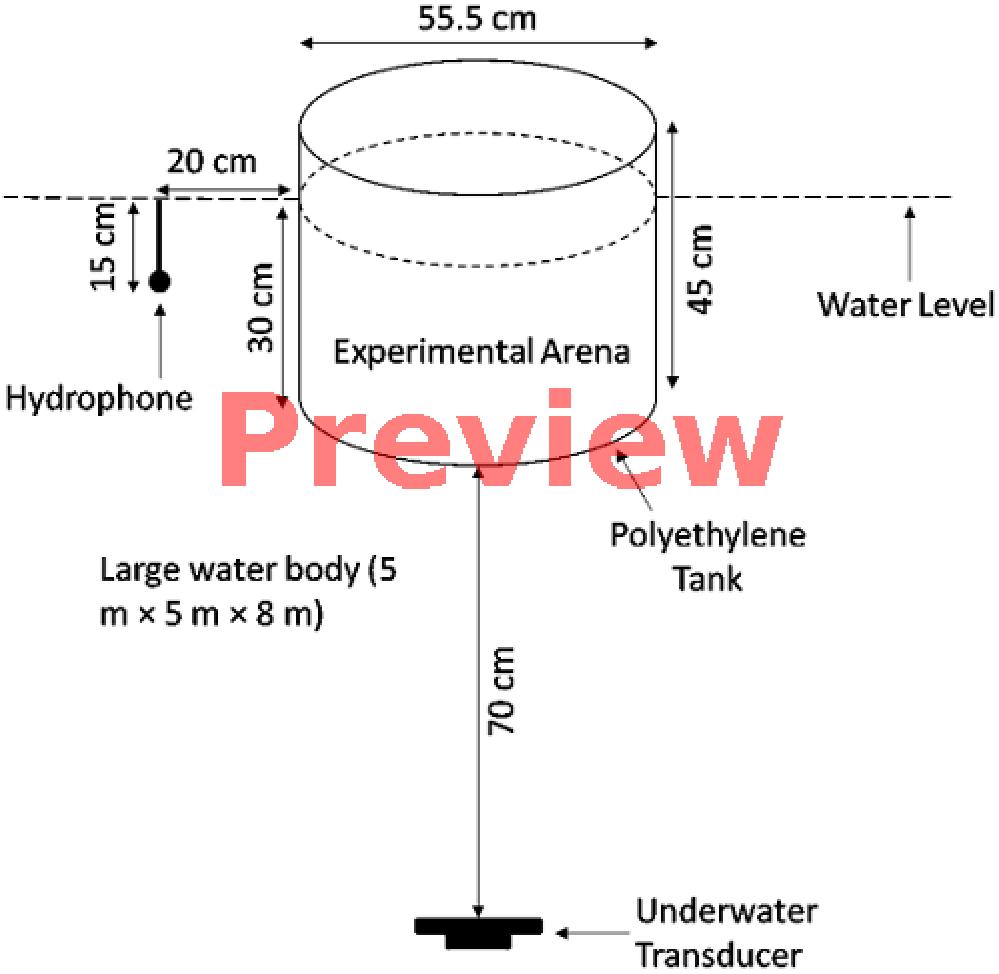

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Fig. 2

The submerged arena (55.5 cm diameter × 45 cm height) inside a large tank of dimensions (8 m length × 8 m width × 5 m depth) in relation to the water level (dotted line, 30 cm water depth). The transducer was suspended 70 cm below the tank, and a hydrophone placed 15 cm below the water level and 20 cm away

Acoustic Stimuli and Sound Mapping

Sinusoidal 1 s tones at five frequencies (400; 600; 800; 1000; 2000 Hz) were produced in MATLAB (Version 2019b, The Mathworks, Inc., Natick, USA) using a laptop connected to a DAQ (NI USB-6212; National Instruments, USA) operating at 25.6 kHz, transmitting the signal through an amplifier (Prosound Power AMP 200; frequency response: 20 Hz–20 kHz), and was emitted via the UW30 underwater transducer. Acoustic stimuli were standardized such that the SPL (125 dB re 1 µPa) was reached in the center of the experimental arena. Use of artificial stimuli allowed for control of the specific acoustic components tested.

The sound pressure field was measured and mapped using a calibrated hydrophone attached to a manual slider (for the in-air tank: 8103, manufacturer-calibrated sensitivity −211 dB re: 1 V μPa, Brüel & Kjær; for the submerged arena: 8105, manufacturer-calibrated sensitivity −205 dB re: 1 V μPa, Brüel & Kjær). Point measurements were recorded at three depths (in-air tank: 7 cm, 13.5 cm, 20 cm; submerged arena: 5 cm, 15 cm, 25 cm). At each depth, measurements were taken 5 cm apart (in-air tank: 80 measurements; submerged arena: 76 measurements). The data capture and stimulus generation were synchronized to facilitate computation of the PA. Both SPL and PA were quantified to create maps of the sound field. The PA, a, may be calculated from the same dataset using a gradient-based approximation:

$$ a=-\frac{1}{\rho}\nabla P, \tag{1} $$

where ρ is the ambient density and ∇P is the pressure gradient (Kinsler et al. *1982*).

The pressure gradient was computed using the measurements of the pressure signal. The root mean square (RMS) of the pressure difference was calculated in three directions (x, y, and z), in which the difference between two pressures was computed and then the RMS of that difference was calculated. The pressure gradient was calculated by dividing by the distance between measurements, while the PA RMS (Eq. 1), in all three directions, was calculated by dividing the pressure gradient by the water density. The total PA RMS was determined by combining the obtained values for all three directions and then expressing the results in decibels (dB re 1 mm s^{-2}).

Data Analysis

All statistical analyses were performed in R (version 3.6.3: https://rstudio.com/), while acoustic maps were produced in MATLAB (version R2019b: https://mathworks.com/). Particle motion and sound pressure residuals followed a Gaussian distribution, determined by visual inspection of qq curves. Two-sided F-tests were conducted to compare variance of PA and SPL data between the in-air tank and submerged arena setups for each frequency. Similarly, two-sided, Welch’s t-tests were used to compare the means of PA and SPL between the submerged arena and in-air tank for each frequency.

To determine if a sound field can be described using a plane wave, an expression for the PA under plane wave conditions was considered, (2). The predicted PA could then be compared to the experimental PA to determine which setup better allowed the stimulus to propagate as a plane wave. For a plane wave with no absorption (assuming no absorption in water over the frequency band of interest here is reasonable; Everest and Pohlmann *2015*), then $u = p/(\rho c)$, where u is particle velocity and c is speed of sound underwater (Leighton *1994*). If the plane wave assumption is satisfied, the gradient in acoustic pressure measured by paired hydrophone measurements in three orthogonal directions can be used to calculate the vector of acoustic particle velocity. For a plane wave, where f is frequency, PA is

$$ a=\frac{p2\pi f}{\rho c}. \tag{2} $$

The SPL and PA are expressed in dB using reference values of 1 μPa and 1 mm s^{-2}, respectively, via:

$$ SPL=20{\log}_{10}\frac{p}{10^{-6}}, \tag{3} $$

$$ PA=20{\log}_{10}\frac{a}{10^{-3}}. \tag{4} $$

The PA computed based on a plane wave assumption was then compared to the experimentally measured PA using the χ^{2}_{red} statistic such that (Andrae et al. *2010*):

$$ {\chi}_{red}^2=\frac{1}{\mathrm{k}}\sum \frac{{\left({PA}_e-{PA}_p\right)}^2}{PA_p}, \qquad (5) $$

where PA_e was the experimental PA, PA_p was the predicted PA (using a plane wave approximation), and k is the degrees of freedom. The closer the ${\chi}_{red}^2$ value to one, the more unified the distributions, hence, the greater the agreement with the plane wave assumption (Andrae et al. *2010*). Thus, for large values of ${\chi}_{red}^2$, it can be assumed that the sound did not propagate as a plane wave.

Results

In-Air Tank Setup

For the in-air configuration the SPL subjectively appeared heterogeneous across the horizontal plane for each frequency (Fig. 3), with greatest variation observed at the highest frequencies (shortest wavelength), i.e., at 1000 Hz and 2000 Hz (Table 1). The mean SPL differed by ≈6 dB between the top and bottom of the tank. The experimental PA was greater than that predicted based on the plane wave assumption, with 400 Hz exhibiting the highest levels of PA (Fig. 3). Had the sound propagated as a plane wave, the PA was predicted to increase with frequency (Table 2); however, the measured PA did not follow this trend. Hence, the two distributions were dissimilar, which resulted in large values of ${\chi}_{red}^2$.

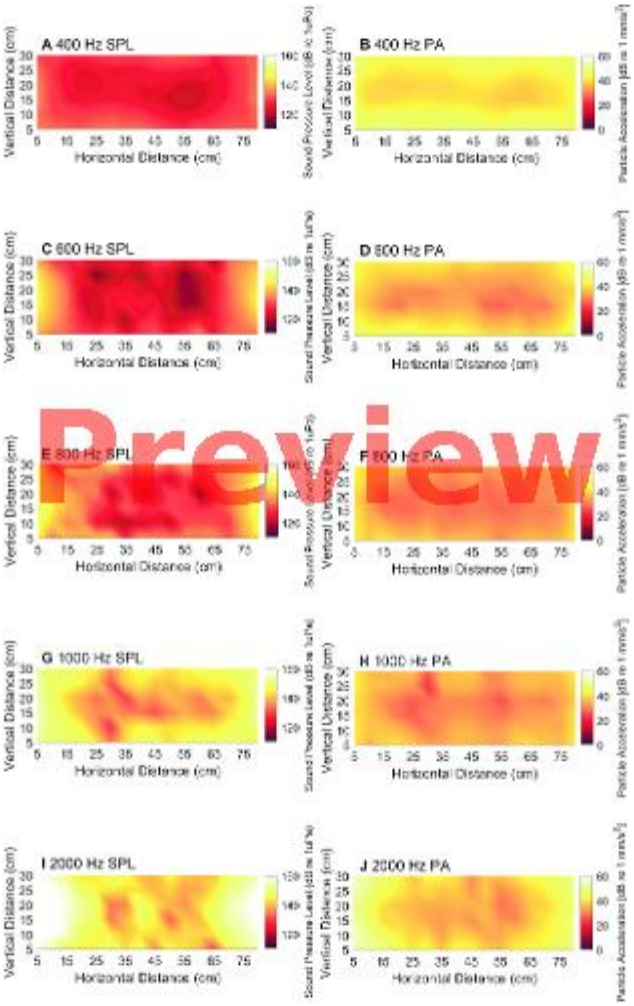

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Fig. 3

SPL maps (**a, c, e, g, i**) and PA maps (**b, d, f, h, j**) (13.5 cm depth) of a 1 s pure tone calibrated at 125 dB re 1 µPa in the center of a rectangular experimental arena (80 cm × 30.8 cm × 30.2 cm) within acrylic in-air tank (300 cm × 30.8 cm × 30.2 cm) at frequencies of 400; 600; 800; 1000; 2000 Hz

Table 1

The mean SPL ± standard deviation of a 1 s pure tone calibrated at 125 dB re 1 µPa in the center of a rectangular experimental arena (80 × 30.8 × 30.2 cm) within acrylic in-air tank (300 × 30.8 × 30.2 cm) at frequencies of 400; 600; 800; 1000; 2000 Hz. Point measurements were taken at 3 depths (7, 13.5, 20 cm). Center SPL refers to the SPL in the center of the tank

Frequency (Hz)	7 cm (dB re 1 µPa)	13.5 cm (dB re 1 µPa)	20 cm (dB re 1 µPa)	Center SPL (dB re 1 µPa)
400	124.3 ± 4.4	128.8 ± 3.4	131.4 ± 2.9	125.0 ± 0.5

600	128.5 ± 7.5	129.3 ± 7.4	134.8 ± 5.6	125.0 ± 1.4
800	134.6 ± 7.6	136.1 ± 9.2	138.6 ± 6.8	125.1 ± 2.8
1000	136.6 ± 8.2	137.7 ± 9.8	144.0 ± 6.2	125.1 ± 6.7
2000	136.5 ± 8.2	137.6 ± 9.8	143.9 ± 6.2	125.0 ± 6.7

Table 2

The mean PA ± standard deviation of a 1 s pure tone calibrated at 125 dB re 1 μPa in the center of a rectangular experimental arena (80 × 30.8 × 30.2 cm) within acrylic in-air tank (300 × 30.8 × 30.2 cm) at frequencies of 400; 600; 800; 1000; 2000 Hz. Point SPL measurements were taken at 3 depths (7, 13.5, 20 cm) and PA (Experimental) was calculated from those values. PA (Predicted) was calculated using the plane wave approximation and the difference between experimental and predicted PA (Experimental – Predicted) was recorded

Frequency (Hz)	**13.5 cm (dB re 1 mm/s^2) Experimental**	**13.5 cm (dB re 1 mm/s^2) Predicted**	**χ^2_{red} In-air**
400	43.3 ± 3.4	12.9 ± 3.4	79.9
600	37.5 ± 5.1	16.8 ± 7.4	42.9
800	33.3 ± 4.3	19.3 ± 7.4	17.0
1000	34.3 ± 4.2	29.7 ± 9.8	4.72
2000	41.0 ± 6.6	35.6 ± 9.8	3.16

Submerged Arena Setup

In contrast to the in-air configuration the SPL in the submerged area was relatively homogeneous across the horizontal plane for each frequency (Fig. 4), with greatest variation observed at 2000 Hz (as expected, given the shorter wavelengths) (Table 3). The mean SPL differed by ≈11 dB between the top and bottom of the tank. The measured PA was lower in value than the in-air tank (Fig. 4). As with the in-air tank, had the sound propagated as a plane wave, the PA was predicted to increase with frequency (Table 2) and the experimental PA follow this trend (except for the lowest frequency considered, 400 Hz), resulting in smaller values of $ {\chi}_{red}^2 $ for 400–1000 Hz compared to the in-air tank (Table 4).

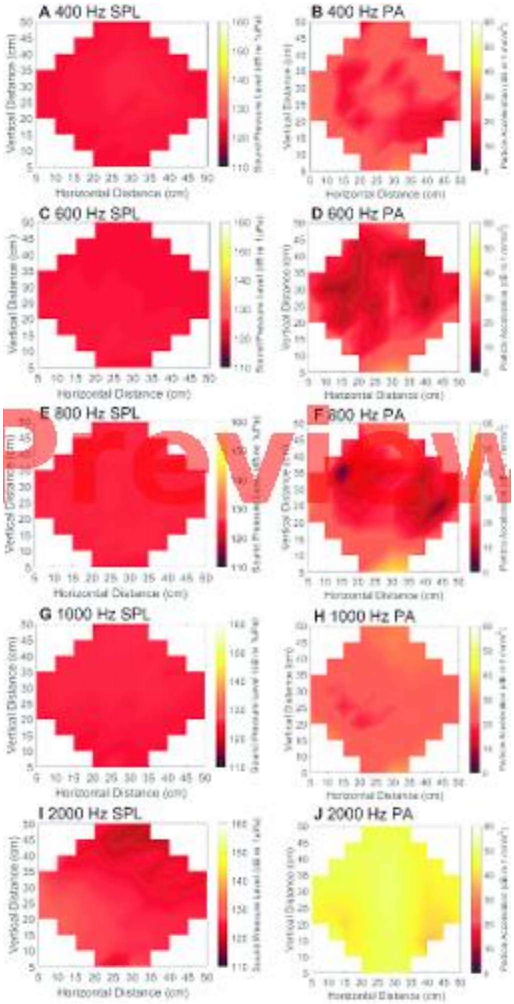

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Fig. 4

SPL maps (**a, c, e, g, i**) and PA maps (**b, d, f, h, j**) (15 cm depth) of a 1 s pure tone in the center of a cylindrical arena (55.5 cm × 45 cm) submerged in a tank (8 m × 8 m × 5 m) at frequencies of 400; 600; 800; 1000; 2000 Hz

Table 3

The mean SPL ± standard deviation of a 1 s pure tone calibrated at 125 dB re 1 μPa in the center of a cylindrical arena (55.5 cm × 45 cm) submerged in a tank (8 × 8 × 5 m) at frequencies of 400; 600; 800; 1000; 2000 Hz. Point measurements were taken at 3 depths (5, 15, 25 cm). Center SPL refers to the SPL in the center of the tank

Frequency (Hz)	5 cm (dB re 1 µPa)	15 cm (dB re 1 µPa)	25 cm (dB re 1 µPa)	Center SPL (dB re 1 µPa)
400	113.8 ± 0.5	124.4 ± 0.4	128.5 ± 0.6	125.0 ± 0.3
600	113.4 ± 0.4	124.3 ± 0.3	128.0 ± 0.6	124.5 ± 0.1
800	114.7 ± 0.4	125.0 ± 0.2	128.4 ± 0.3	125.0 ± 0.1
1000	114.9 ± 0.6	124.9 ± 0.5	128.3 ± 0.5	125.0 ± 0.3
2000	114.9 ± 1.8	124.7 ± 2.4	124.0 ± 2.6	125.4 ± 0.6

Table 4

The mean PA ± standard deviation of a 1 s pure tone calibrated at 125 dB re 1 μPa in the center of a cylindrical arena (55.5 cm × 45 cm) submerged in a tank (8 × 8 × 5 m) at frequencies of 400; 600; 800; 1000; 2000 Hz. Point SPL measurements were taken at 3 depths (5, 15, 25 cm) and PA (Experimental) was calculated from those values. PA (Predicted) was calculated using the plane wave approximation and the difference between experimental and predicted PA (Experimental – Predicted) was recorded

Frequency (Hz)	15 cm (dB re 1 mm /s^2) Experimental	15 cm (dB re 1 mm /s^2) Predicted	χ^2_{red} Submerged
400	21.1 ± 3.8	8.5 ± 0.4	21.4
600	17.9 ± 5.6	11.9 ± 0.3	5.81

800	20.3 ± 6.8	15.1 ± 0.2	5.02
1000	24.8 ± 3.5	16.9 ± 0.5	4.57
2000	45.3 ± 3.1	22.7 ± 2.4	24.5

Comparison of Setups

No difference in the variance of experimental PA was detected between the in-air tank and the submerged arena for frequencies of 400, 600, and 1000 Hz ($F = 1.450 – 0.788$; $p = 0.095 – 0.381$) but a difference in variance was detected for 800 and 2000 Hz ($F = 4.500 – 0.395$; $p = <0.001$). The type of setup had an effect on the variance of SPL for all frequencies and depths ($F = 5.533 – 2268.7$; $p = <0.001$). Results suggested that the SPLs of the in-air setup were more heterogeneous than the submerged arena.

Welch's *t*-tests were carried out, detecting experimental PA to differ between the two setups, with PA being higher in the in-air tank than the submerged arena for 400–1000 Hz ($t = 14.608–40.527$; $p = <0.001$) and lower for 2000 Hz ($t = −5.254$, $p = < 0.001$). Additionally, Welch's *t*-tests detected that the setup influenced the SPL at all frequencies and depths ($t = 6.559–28.299$; $p = <0.001$). The in-air tank setup exhibited higher mean SPLs at all depths compared to the submerged arena setup.

The predicted PA was calculated for both the in-air tank and the submerged arena setup, which determined the PA had the sound propagated as a plane wave. The predicted PA was then compared to the experimental PA using the \({\chi}_{red}^2 \)statistic. For the in-air tank, the difference between the predicted PA and experimental PA was on average 15.0 ± 11.5 dB. The submerged arena had a smaller difference between the experimental and predicted PA at 10.9 ± 8.1 dB on average, depending on the frequency. The χ *2red* was closer to 1 for the submerged arena than the in-air tank for all frequencies except 2000 Hz. This suggests that the plane wave assumption provides a better approximation for the PA in the submerged arena than in the in-air tank.

Discussion

Small tanks have been a subject of debate among underwater bioacoustics researchers, due to their sound field complexity, starting with the classic work of Parvulescu (*1964*, *1967*; also see Rogers et al. *2016*). If a laboratory study is necessary (due to lack of access to the field or to remove a variable that may be present in such conditions), the sound field used in this study is valid. This study consisted of two experimental tank setups and categorized a novel setup in terms of its acoustic validity, as well as experimental control. The SPL heterogeneity was highest in the in-air tank, followed by the submerged arena, indicating that the submerged arena setup is an ideal substitute for creating a homogeneous sound field. The PA was also higher in the two in-air tanks than the submerged arena, suggesting that the submerged arena tank walls were acoustically transparent, hence reducing boundary reflections. When the experimental PA was compared to a PA predicted using a plane wave equation, the submerged arena provided a better approximation. This study provided an alternative experimental setup for performing bioacoustics studies on fish that gave greater control over the stimulus that a fish experiences in lab-based experiments in terms of SPL and PA.

For open-water fish species, experimental conditions should replicate far-field acoustics in which the PA and SPL increase proportionally (Slabbekoorn *2016*). However, if in-air tanks were used for open-water species, the PA would be disproportionally larger than SPLs compared to those open waters (Parvulescu *1967*; Rogers et al. *2016*). Therefore, the small in-air tanks would not be representative of an open-water habitat and may lead to misleading results (Popper and Hawkins *2018*). Nonetheless, fish species inhabiting shallow waters would encounter inhomogeneous sound fields due to turbulence (Tonolla et al. *2009*), close top and bottom boundaries, and volume reverberation (Hawkins and Myrberg *1983*; Lynch and Newhall *2017*). However, we recommend that if non-uniform sound fields were required for a particular study, it would be more valid to modify a homogeneous sound field to the desired inhomogeneity. This approach would ensure the replicability of the sound field.

The results of this study are of particular importance to hearing experiments that were historically undertaken in small, in-air tanks. However, it is also recommended that lower frequencies are also tested, since this study used frequencies above 400 Hz, which is higher than the sensitive frequencies for many fish. While the effect of small in-air tank acoustics on hearing studies has been discussed extensively elsewhere (see Rogers et al. *2016*), the results from this study further suggest that some hearing experiments may be invalid due to the setup and the complexity of the sound field. In such conditions, the received level and source level may have been contradictory..

The submerged arena vastly improved the PM and SPL aspects of the sound field, primarily by reducing the average PM and reducing both SPL and PM variance. Submerging the tank in water removed air as a surrounding medium which meant the impedance and reverberation, factors that increase sound field complexity, were minimized (Rogers et al. *2016*). When comparing the submerged arena to other setups, the behavioral validity remains low compared to field-based experiments but retains high experimental control, practicality, and feasibility (Slabbekoorn *2016*). Compared to field-based methodologies, the acoustic validity is lower given that there was some scattering from the air-water interface, so it would be wise for a future study to compare the sound field as the submerged tank is placed further from the surface boundary (although this will make sound field mapping more difficult). An additional consideration is the effect of the swim bladder and the fish itself on the sound field (see Chapman and Hawkins *1973*) and hence requires further investigation. However, there is a vast improvement to sound field homogeneity compared to small tank studies since a plane wave approximation was feasible. To be specific, the submerged arena used here, with its acoustically transparent walls, allowed the source to be placed outside of, and so at a greater range from, the working arena, which tended to decrease the radius of curvature of the wavefronts in the arena and so make the use of Eq. (2) (with its inherent plane wave assumption). This is an important consideration, especially if there is no independent way to validate the estimated PA, as is often the case in such studies. It is recommended that when cost, practicality, and experimental control limit the use of in situ studies, a submerged tank would be a suitable alternative.

Conclusion

This study investigated two experimental setups: a ‘typical’ setup of a rectangular acrylic arena surrounded by air and placed on concrete blocks with two transducers situated in the arena and a setup of a cylindrical arena submerged in a large water tank with a speaker situated underneath. A submerged arena setup was chosen to reduce sound field inhomogeneity so that the level received by the fish is constant and known to the experimenter, and the study is replicable. The in-air tank exhibited an inhomogeneous field with high levels of PA, while the submerged arena possessed a homogeneous sound field with PA measurements satisfying the plane wave approximation to a larger degree. While the behavioral validity of the setup does not compare with in situ studies, submerging an experimental arena greatly improves the sound field homogeneity essential for acoustic and behavioral replicability in bioacoustics studies with fish.

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