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RESEARCH ARTICLE

Graded behavioral responses and habituation to sound in the common cuttlefish *Sepia officinalis*

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ABSTRACT

Sound is a widely available and vital cue in aquatic environments, yet most bioacoustic research has focused on marine vertebrates, leaving sound detection in invertebrates poorly understood. Cephalopods are an ecologically key taxon that likely use sound and may be impacted by increasing anthropogenic ocean noise, but little is known regarding their behavioral responses or adaptations to sound stimuli. These experiments identify the acoustic range and levels that elicit a wide range of secondary defense behaviors such as inking, jetting and rapid coloration change. Secondarily, it was found that cuttlefish habituate to certain sound stimuli. The present study examined the behavioral responses of 22 cuttlefish (*Sepia officinalis*) to pure-tone pips ranging from 80 to 1000 Hz with sound pressure levels of 85–188 dB re. 1 μPa rms and particle accelerations of 0–17.1 m s^{-2}. Cuttlefish escape responses (inking, jetting) were observed between frequencies of 80 and 300 Hz and at sound levels above 140 dB re. 1 μPa rms and 0.01 m s^{-2} (0.74 m s^{-2} for inking responses). Body patterning changes and fin movements were observed at all frequencies and sound levels. Response intensity was dependent upon stimulus amplitude and frequency, suggesting that cuttlefish also possess loudness perception with a maximum sensitivity around 150 Hz. Cuttlefish habituated to repeated 200 Hz tone pips, at two sound intensities. Total response inhibition was not reached, however, and a basal response remained present in most animals. The graded responses provide a loudness sensitivity curve and suggest an ecological function for sound use in cephalopods.

KEY WORDS: Bioacoustics, Cephalopod, Hearing, Noise, Loudness, Invertebrate, Ear, Statocyst, Lateral line

INTRODUCTION

Sound in aquatic environments is a widely available cue that many marine vertebrates use during vital biological activities such as foraging, predator detection, mate attraction and habitat selection (Webster et al., 1992; Fay and Popper, 1998; Au et al., 2000). Consequently, for vertebrates, sound detection is considered a primary sensory modality and an important component of vital intraspecific interactions and a key way to detect the surrounding environment. The ability of marine invertebrates to detect and potentially use sound is far less understood (Budelmann, 1992a; Budelmann, 1992b; Mooney et al., 2012). This is somewhat surprising given their relative abundance and central role in many marine ecosystems.

Yet, a growing body of literature suggests that marine invertebrates respond to sound in a variety of ways. For example, coral reef invertebrates (crabs and coral larvae) may swim toward or away from reef sounds, with the actual direction being taxon specific (Vermeij et al., 2010; Simpson et al., 2011). Reef sounds from certain habitats can generate settlement behaviors and increased rates of metamorphosis (Stanley et al., 2010; Stanley et al., 2012). Perhaps not surprisingly, variations in the frequencies and levels of these sounds can affect whether the behavior is induced (Simpson et al., 2011; Stanley et al., 2011). However, thresholds have rarely been established and we still know little regarding the frequencies to which most invertebrates respond. Furthermore, it is vital to quantify acoustic particle motion, a stimulus often overlooked. Both sound pressure and acoustic particle motion are generated by sound sources, but it is particle motion [i.e. the back-and-forth hydrodynamic flow from the motion of the sound emitter (Gade, 1982; Au and Hastings, 2009)] that is the likely stimulus for most marine animals without compressible air cavities (Mann et al., 2007; Mooney et al., 2010; Popper and Fay, 2011). Despite a burgeoning literature, there is a poor understanding of the frequencies and levels of sounds that generate functional behavioral responses in invertebrates.

Cephalopods offer a unique means to quantify the frequency range and sound levels that generate behavioral responses for several reasons. First, the potential behavioral responses of several species, such as the common cuttlefish, *Sepia officinalis* Linnaeus 1758, are both dynamic and well described (Hanlon and Messenger, 1996). Previous behavioral studies have shown that these cuttlefish exhibit a range of responses to sensory stimuli, including changes in body patterning, locomotor activity, jetting and inking events (Hanlon and Messenger, 1996). Second, these behavioral responses show a gradation in intensity, from primary defense responses (usually crypsis or camouflaging against the background), to secondary defenses such as deimatic behaviors used to deter the potential predator, and ultimately flight responses involving jetting and inking (Hanlon and Messenger, 1988; Langridge et al., 2007; Langridge, 2009; Staudinger et al., 2011). A similar gradation in response intensity may be generated by acoustic stimuli (Fewtrell and McCauley, 2012). Finally, many cephalopods occupy central positions in food chains; thus, understanding their sensory ecology is required to accurately determine relationships between this taxon and other marine species, and could provide indications on how other invertebrates may use sound.

The statocyst is generally considered the primary sound detection organ in cephalopods (Budelmann, 1990; Budelmann, 1992a), although peripheral hair cells may play a role in detecting local water movements (Bleckmann et al., 1991; Coombs et al., 1992). With regard to acoustic stimuli, the statocyst likely acts as an accelerometer in response to the vibratory particle motion component of sound (Budelmann, 1990; Packard et al., 1990; Mooney et al., 2010). Besides the hair cells in the statocysts,

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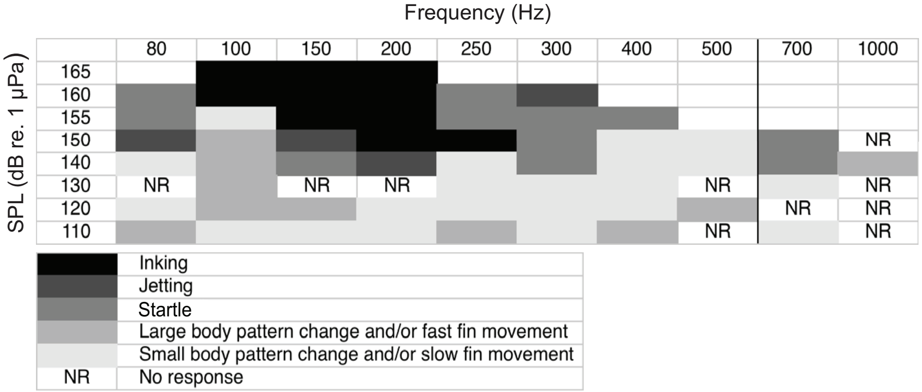

SPL (dB re. 1 µPa)	80	100	150	200	250	300	400	500	700	1000
165		■	■	■						
160	▦	■	■	■	▦	▩				
155	▦	░	■	■	▦	▦	▦			
150	▩	▨	▩	■	■	▦	░	░	▦	NR
140	░	▨	▦	▩	░	▦	░	░	▦	▨
130	NR	▨	NR	NR	░	░	░	NR	░	NR
120	░	▨	▨	░	░	░	░	▨	NR	NR
110	▨	░	░	░	▨	░	▨	NR	░	NR

■	Inking
▩	Jetting
▦	Startle
▨	Large body pattern change and/or fast fin movement
░	Small body pattern change and/or slow fin movement
NR	No response

Fig. 1. Matrix of the behavioral responses of an individual cuttlefish to different sounds. The matrix reflects the stimuli presented as part of the experimental design. The responses shown are from 1.5 year old cuttlefish for frequencies between 80 and 500 Hz, and from a different, 1 year old animal for frequencies of 700 and 1000 Hz. The blank cells indicate sound combinations that were not played because of technical limitations of the set-up. NR, no response. The control is not represented in the matrix. SPL, sound pressure level.

common cuttlefish also have eight lines of epidermal hair cells running over their head and arms that are able to detect local water movements generated by a vibrating sphere (Budelmann and Bleckmann, 1988; Komak et al., 2005).

There is some anecdotal evidence suggesting that cephalopods respond to sounds such as tapping on the tank wall (Baglioni, 1910; Dijkgraaf, 1963). Other observational evidence includes cephalopods swimming away from sound-generating predators in the sea (Hanlon and Budelmann, 1987). More recently, conditioned responses were generated in common octopus (*Octopus vulgaris*), squid (*Loligo vulgaris*) and cuttlefish (*S. officinalis*) using low-frequency acceleration stimuli (Packard et al., 1990). Juvenile *S. officinalis* exhibited body patterning changes and locomotor responses when exposed to water movements ranging between 0.01 and 1000 Hz (Komak et al., 2005), and octopus showed changes in respiratory rates when presented with sound stimuli between 50 and 150 Hz (Kaifu et al., 2007). Furthermore, there are suggestions that anthropogenic noise may impact cephalopod behavior or anatomy (André et al., 2011; Fewtrell and McCauley, 2012). Understanding the frequency ranges and sound levels that generate behavioral responses, whether they adapt (habituate) and the types of behavioral responses elicited would help us to evaluate the likely influences of noise on cephalopods.

Accordingly, the aim of this study was to quantify the sounds that generate behavioral responses and identify the potential behaviors elicited. Animals were presented with tones that varied in both frequency and sound level, and response types were quantified. The three main goals were to: (1) determine the frequency range and sound levels to which behavioral responses are observed, (2) describe and quantify the types of responses and their occurrence rates, and (3) investigate the potential for habituation to repeated sound stimuli. In addressing these goals, both sound pressure and particle acceleration were quantified.

RESULTS

Acoustic frequency range and sensitivity

All animals showed clear behavioral responses to acoustic stimuli (Figs 1, 2), and the intensity of the response was associated with the amplitude and the frequency of the signal. Multiple response types were elicited (Table 1). Responses occurred at all frequencies tested; occurrence rates and response types were dependent upon both the frequency and sound level received (Fig. 1). Some individual variations in response intensities were observed but the general pattern of response intensities was conserved. The greatest intensity responses (i.e. inking; Fig. 2) were found at the highest sound levels, typically between 100 and 300 Hz. At lower sound levels, response intensity typically decreased to jetting, startle, large body patterning changes and/or fast fin movements, and small body patterning changes and/or slow fin movements. The no-sound controls most often showed 'no response', but small and large fin movements and/or body pattern changes were also observed. These responses were more often noted in the more active animals. More frequently, these animals would swim and change body pattern in their housing tanks (outside of the experiments) where they might interact with other animals and respond to prey presentation during feedings. Inking, jetting and startle were not observed in the controls.

The sound parameter matrix did not take into account the distance between the animal and the speaker, meaning that the sound levels in Fig. 1 are the calibrated sound levels at 20 cm from the speaker, not the sound levels actually received by the animal. This resulted in discrepancies in the observed pattern of response intensities. For example, small body pattern changes and/or slow fin movements are often placed at higher sound levels than big body pattern changes and/or fast fin movements (Fig. 1).

Corrections for the distance between the animal and the speaker were made and the behavioral responses were plotted relative to the actual received particle acceleration (Fig. 3) for each sound trial

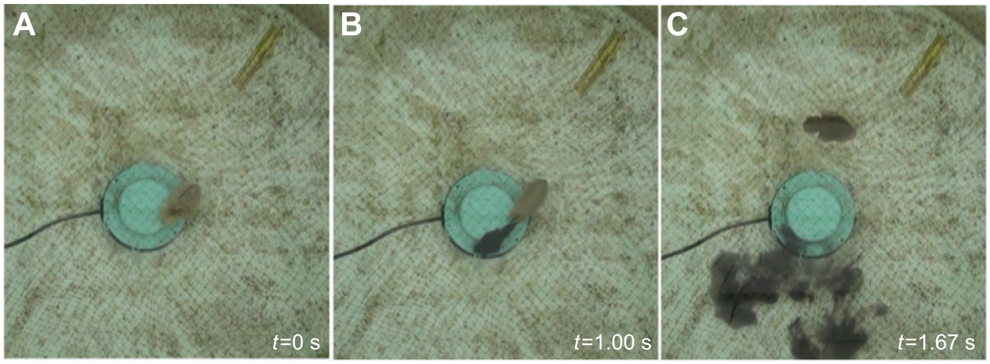

Fig. 2. Types of behavioral responses to sound. These frames are extracted from one test and illustrate how different behavioral responses can be combined. (A) Cuttlefish at rest in the experimental tank before the sound stimulus. The median arms are dark and are held backward over the head. (B) Jetting and inking. (C) Large body pattern change (darkening) and fast fin movements resulting in a displacement of the animal after it has jetted away.

Table 1. Overview of the types of response and their intensity used to score the behavioral responses of *Sepia officinalis* to sound stimuli

Response type	Intensity	Description
No response	–	No change in behavior observed, no acceleration or deceleration in fin movement, no body pattern change or flickering of chromatophores, no displacement.
Body pattern change	Small	Body pattern change covering less than half the body area.
	Big	Body pattern change covering at least half the body area, includes dark flashing, bleaching, deimatic, etc.
	Deimatic	Body pattern including some or all of the following: flattened body shape, paling of the skin, paired dark mantle spots, dark fin line, dark eye rings, pupil dilation.
Fin movements	Slow	Slow fin undulations resulting in slow displacements (undulation rate estimated to be less than 1 Hz).
	Fast	Intense fin undulations resulting in rapid, marked displacements (undulation rate estimated to be more than 1 Hz).
Startle	Small	Small contraction of the mantle and/or arms, often followed by slow fin movements with or without displacement.
	Big	Big, marked contraction of the mantle and arms, usually followed by big displacements and/or jetting.
	Stereotyped	Arm twitch, sometimes with a small mantle contraction. The arms go back to their initial position immediately after the response. In some cases, the arms only twitch at the tips and a contraction of the pupils is observed. No displacement.
Jetting	Small	Small jet(s), distance covered is less than two body lengths, speed is relatively slow. The number of jets was also recorded.
	Big	Big jet(s), distance covered is at least two body lengths, displacement is fast. The number of jets was also recorded.
Inking	–	Expulsion of ink. The number of inking events was also recorded.
Other	Elongating	Body is stretched along the longitudinal axis, the arms, especially, are stretched.

(pressure data are shown in the supplementary material). Only the most intense response for each trial was plotted; i.e. if the animal showed several responses during a test, only the highest scoring response was plotted (inking in the case of Fig. 2). Cuttlefish escape responses (inking, jetting, startle) were highly dependent on the sound frequency and level. Inking was only observed for sounds between 80 and 300 Hz, and above 0.73 m s^{-2} (particle acceleration) and 140 dB [sound pressure level (SPL) presented in dB re. 1 μPa rms]. Jetting and startle responses were observed primarily between the same frequencies, with occasional incidences at higher frequencies. These responses also occurred predominantly above 0.01 m s^{-2} (above 140 dB) with a few occurrences at lower sound levels, stretching the range of particle acceleration eliciting those responses by an order of magnitude compared with inking. No escape responses were observed below particle accelerations of 3.3×10^{-3} m s^{-2} or 110 dB. Less intense responses (body patterning changes and fin movements) were more widespread along both the frequency and sound intensity range and had much lower mean acceleration levels (dashed lines in Fig. 3 and supplementary material Fig. S1). The less intense responses were seen at acceleration levels down to 4×10^{-4} m s^{-2} and SPLs as low as 85 dB. The absence of response (no response) was typically found at lower sound levels, similar to the levels eliciting body patterning changes and fin movements.

The mean SPL and particle acceleration eliciting behavioral responses were not constant over the frequency range (Fig. 4). The lowest sound levels eliciting a response were found at 150 Hz, regardless of whether they were measured as particle acceleration or sound pressure. At this frequency, animals demonstrated responses to sound stimuli at a mean particle acceleration of 0.025 m s^{-2} (and mean SPL of 124 dB), and the elicited response was a small body

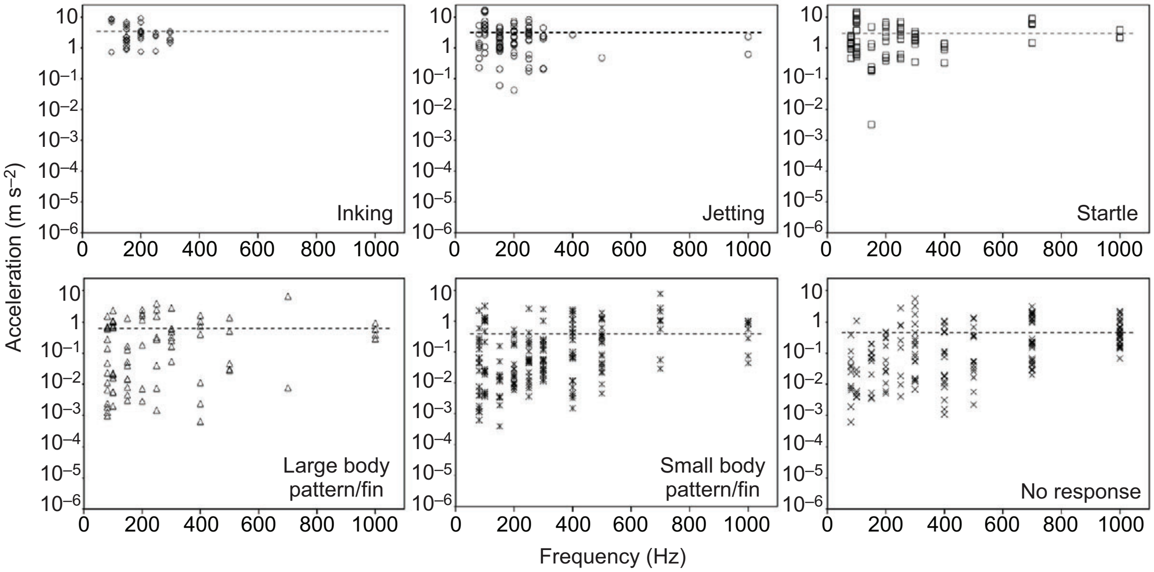

Fig. 3. Received particle accelerations and the behavioral responses they elicited. Only the highest scoring behaviors for each sound test are represented here (i.e. not all occurrences of each response type are shown). Large body pattern/fin: large body pattern change and/or fast fin movements; small body pattern/fin: small body pattern change and/or slow fin movements. The dashed lines represent the mean acceleration value for that response.

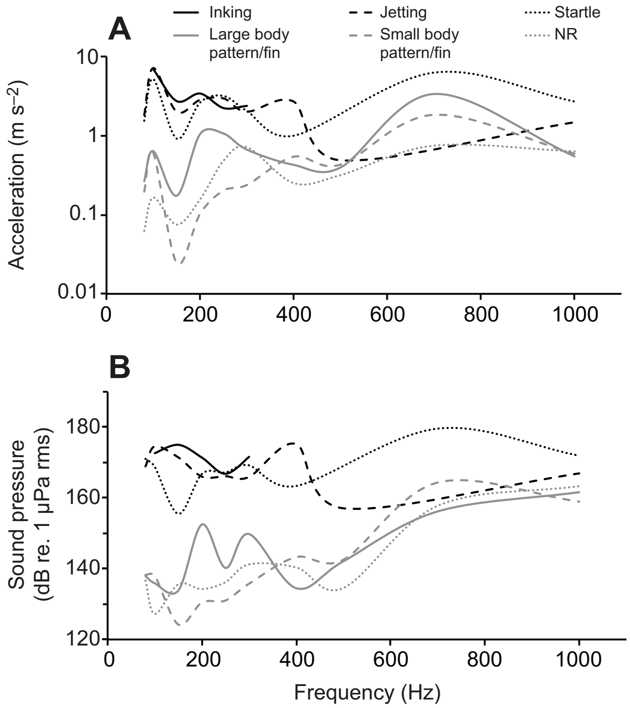

Fig. 4. Mean behavioral responses. (A) Acceleration; (B) sound pressure. Only the highest scoring behaviors for each sound test are represented here. At lower frequencies (below 500 Hz), the escape responses (jetting, inking and large body pattern change) were elicited at higher sound levels. Above 500 Hz, a relatively high sound level was needed to induce any type of response.

patterning change and/or small fin movement. The absolute lowest sound levels eliciting a response at 150 Hz were 4×10^{-4} m s^{-2} and 85 dB; the observed behavior in these cases was a small body patterning change and/or fin movement. In contrast, 1000 and 700 Hz required relatively high sound levels to elicit responses from the animals (Figs 1, 4).

There were no changes in response rates while the animals were subject to the conditions in the matrix (including across the 11 consecutive days or within single test days with four tests per day, at least 20 min between each test). For example, we were concerned that animals might have reacted less at the end of the 2 weeks of testing (i.e. a cuttlefish getting a 300 Hz/140 dB sound on day 3 might react more than a cuttlefish getting that same sound on day 10 because the latter had already been exposed to multiple tones for 9 days). However, response types and occurrences showed no consistent pattern with respect to the order of sound presentations. This suggests that: (1) cuttlefish behaviors were not influenced by the prior exposures; thus, it is possible the animals did not learn or otherwise anticipate the sound presentation when signals were presented in this randomized order and schedule; and (2) the repeated sound presentations did not impact on their hearing enough to change their responses. Consequently, individual sound presentations were considered independent trials.

Habituation to repeated sounds

While response rates did not change in the random matrix, which spread sound trials over several days, habituation to acoustic stimuli was observed when identical sounds were presented closer in time. When tones of the same source level and frequency were presented every minute for 30 min, the number of animals showing escape responses (inking and jetting) decreased logarithmically as the number of repeated stimuli increased (Fig. 5). This was true for both higher and lower sound levels although higher sound levels tended to reflect less variation in the number of animals responding and, correspondingly, higher regression-based r^2 values (Table 2). For example, inking response occurrence rates were significantly related to trial number for both the higher and lower sound levels, but higher sound levels produced a higher r^2 value (r^2 values for high and low sound levels were 0.6 and 0.42, respectively; see Table 2). Jetting responses, also tied to trial number, occurred more often in the early trials, allowing for a steeper decline in response rates for both high and low sound levels. Occurrence rates decreased significantly with increasing trial number (r^2 values for high and low sound levels were 0.72 and 0.70, respectively). Similar trends were seen for the large body patterning changes as well, but with greater overall variation (r^2=0.25 at the higher sound level; r^2=0.49 at the lower sound level). Startle responses, fin movements and smaller body patterning changes showed reverse trends with slight increases in occurrence rates as trial number increased. This was likely because the escape responses tended to dominate at the beginning of test series (only the highest scoring behavior was taken into account for each trial); as trial number increased and habituation set in, the lower intensity responses became more prevalent.

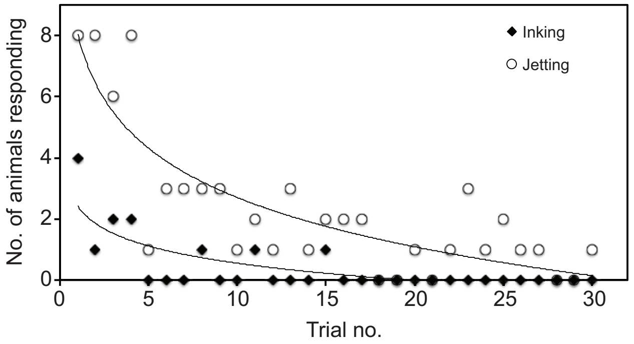

Fig. 5. Habituation to a repeated sound stimulus. Data were collected using a 200 Hz tone at 165 dB (calibrated sound pressure), which was presented every minute for 30 consecutive trials. The occurrence of both response types (inking and jetting) decreased logarithmically (for details, see Table 2, high sound level). N=10 cuttlefish.

The differences in particle acceleration shown in Fig. 6 provide an indication of the movements of the animal because the received acceleration level depended on the distance of the animal to the speaker. Cuttlefish often settled themselves near the speaker, at the bottom of the netted space, so the first trial of each test series tended to be at a relatively high received level (Fig. 6A, black symbols). The animal in Fig. 6A then moved higher in the water column, away from the speaker, and received a relatively lower sound level in the second trial (the particle acceleration is lower). The cuttlefish subsequently moved around in the tank and finally settled back down after 5–10 exposures (reflected in the more or less constant sound level from trial 10 onward). This pattern is also noticeable in Fig. 6A (gray symbols) and 6B.

Total response inhibition was never reached; individuals repeatedly exhibited a ‘stereotyped startle’ response. The order in which the sounds were presented (i.e. higher intensity sound on the first or second test day) and the age of the animals did not have an effect on the observed decrease in response type. Greater variation in the responses given by different animals was also seen in the early trials, but sound levels were also more variable as the animal tended to move around in the sound field as a result of the acoustic stimuli.

Table 2. Logarithmic regression statistics to evaluated response occurrence rates versus trial number

Sound level	Response type	Line equation	r^2	*P*	*n*
High	Jetting	$y=-2.32\times\ln(x)+8.03$	0.72	<0.001	30
	Inking	$y=-0.81\times\ln(x)+2.42$	0.6	<0.001	30
	Large color change	$y=-0.78\times\ln(x)+3.97$	0.25	<0.05	30
Low	Jetting	$y=-1.72\times\ln(x)+6.16$	0.7	<0.001	30
	Inking	$y=-0.50\times\ln(x)+1.54$	0.42	<0.01	30
	Large color change	$y=-0.99\times\ln(x)+3.74$	0.49	<0.001	30

n, number of trials (10 animals for each trial).

DISCUSSION

Acoustic frequency range and sensitivity

The primary aim of this research was to address the frequency range and sound levels that induce behavioral responses in a cephalopod, the common cuttlefish. This work provides the only unconditioned, sound-mediated behavioral response data set for cephalopods, and is the only work that describes both the range and sensitivity of such responses for marine invertebrates. The data may be applicable for evaluating the auditory scene that some cephalopods may utilize, and help define the noise conditions that may impact these animals.

The sound levels generating behavioral responses in this study were quite low, often lower than the physiological thresholds previously measured in cephalopods. Body pattern changes and fin movements were observed at the lowest sound levels, as low as 10^{-4} m s^{-2} and down to 85 dB. Neurophysiological responses in longfin squid and common octopus were generated using slightly higher amplitude signals [between 10^{-3} and 10^{-4} m s^{-2} (Kaifu et al., 2008; Mooney et al., 2010)]. The differences between the physiology and behavior results could reflect that the evoked potential methods are not as sensitive as the animal's auditory system and these behavioral metrics. Or there could be taxonomy-based differences as this study used cuttlefish, while Kaifu et al. (Kaifu et al., 2007; Kaifu et al., 2008) and Mooney et al. (Mooney et al., 2010; Mooney et al., 2012) used octopus and squid species. Yet, Packard et al. (Packard et al., 1990) used classical conditioning to address *S. officinalis* sound detection, and response thresholds were still two orders of magnitude higher than here. This suggests that *S. officinalis* is more sound sensitive than previously thought. Furthermore, the unconditioned method used here provides a robust way to address the behavioral response range and apparent sensitivity for this species.

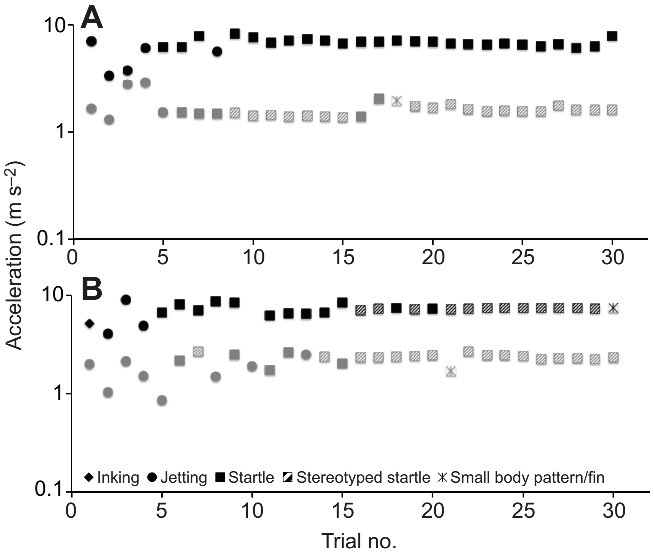

Fig. 6. Succession of behavioral responses of two individual cuttlefish. A 200 Hz tone was presented every minute for 30 consecutive trials. (A) An old animal (1.5 years old), (B) a young animal (6 months old). Black symbols represent the responses to the first test series; gray symbols represent the responses to the second test series.

The overall frequency range and upper limit that generated responses was somewhat greater than in previous acceleration-based cephalopod sound detection studies (Packard et al., 1990; Kaifu et al., 2008; Mooney et al., 2010), but the results were similar to those of many fish without auditory specializations (Popper and Fay, 2011). This reinforces the notion that cephalopods, like many fish, have an accelerometer-like 'auditory' system that detects the particle motion component of sound stimuli. Furthermore, cephalopod auditory scenes and sound use may be very similar to fish without specializations.

Mean response levels fluctuated with stimulus frequency. To some extent, this may be the result of greater sensitivities at lower frequencies. These variations may also be due to sound reflections and interferences linked to the size of our experimental tank. In small tanks, sound does not attenuate as in the free field, and despite the detailed calibrations conducted here it is impossible to determine the exact levels received by a moving animal for every location within the tank. However, the variations may also reflect individual differences in auditory or behavioral response thresholds. Such variation was evident from general observations of the animals and is reflected within the individual data (e.g. Fig. 6).

The occurrence of escape responses was strongly linked to the characteristics of the sound stimulus. For example, inking was only found at lower frequencies and higher sound intensities. Jetting was also only found at the higher sound levels. Yet, all stimuli had relatively rapid rise times and short onsets of the stimuli (tens of milliseconds) suggesting these were not vital to inducing the escape responses. The link to sound intensity suggests that sound level could provide some behavioral relevance to the animals, and that higher levels infer closer predators, thus inducing the escape behaviors. At a more basic level, hearing could be a mechanism for predator detection in these animals. This idea of predator detection is reinforced by the observation of deimatic displays in response to some of the acoustic stimuli. The deimatic display is usually elicited by visual stimuli, e.g. a model of a predator (King and Adamo, 2006; Cartron et al., 2013) or an actual predator (Langridge et al., 2007; Staudinger et al., 2013), with the purpose of deterring said predator. The observation of deimatic displays in the absence of a visual stimulus suggests that sound could play a role in predator detection by cuttlefish, as surmised by Hanlon and Budelmann (Hanlon and Budelmann, 1987).

The behaviors exhibited were clustered relative to frequency and received levels (Fig. 3). Higher levels and lower frequencies induced escape responses (as noted above) and more moderate responses (body pattern changes and fin movements) were observed at lower sound levels and higher frequencies. This trend generally follows what we know regarding cephalopod hearing: they detect lower frequencies better, suggesting a sensation level response curve for these behaviors. The clustering also indicates a potential for the perception of loudness in the common cuttlefish (and perhaps other cephalopods); that is, the behavioral response curves (Figs 4, 5) could be taken as preliminary loudness sensitivity measures. As in several other studies (Stebbins, 1966; Kastelein et al., 2011), these assessments would be subjective and based on certain response characterizations, and would probably not be as accurate as protocols aimed specifically at generating loudness curves (Finneran and Schlundt, 2011). Yet, *S. officinalis* appears to differentially respond to acoustic stimuli based upon relative perceived sound levels, not solely absolute values.

Overall, the dynamic range of potential responses that cuttlefish can generate in response to acoustic stimuli are relatively well characterized in regard to their behavioral and ecological relevance in other contexts (Hanlon and Messenger, 1996). These prior descriptions of behaviors and the clarity of the responses seen during this study indicate cuttlefish are a suitable subject for future bioacoustic studies.

Habituation to repeated sounds

All tested cuttlefish showed habituation to repeated stimuli. Habituation was noted by a logarithmic decrease in the occurrence of certain responses over the course of 30 exposures (30 min) of repeated 200 Hz tone stimuli. This decrease was notable in the more dramatic escape responses (inking and jetting), and for large body patterning changes; this pattern of habituation is similar to that reported in the squid *Lolliguncula brevis* (Long et al., 1989). It was significant across both sound levels, suggesting the robustness of this form of habituation. The decrease in response intensity was more marked at lower sound intensities; this is in agreement with one of the characteristics of habituation described by Rankin et al. (Rankin et al., 2009): weaker stimuli generate more rapid and/or more pronounced habituation.

Similar to the first experiment on acoustic frequency range and sensitivity, escape responses were initiated by relatively higher intensity stimuli (likely of greater sensation level); but in this experiment, earlier signals also showed a greater response rate. These evasion responses suggest that the cuttlefish initially reacted to the stimulus as they would react to a predator or other form of danger, and that sound detection could be a mechanism for predator detection in these animals. After several exposures and no imminent threat, the number of escape responses decreased, suggesting the cuttlefish were able to filter out the ‘irrelevant’ acoustic stimuli, allowing for a refocusing of sensory mechanisms.

This present study is one of the few measuring habituation in cephalopods and the only one focusing on habituation to acoustic stimuli. Previous studies using visual stimuli in squid showed a sharp decrease in the number of jetting responses over the first 5 min of exposure but total inhibition of responses was not observed and the squid continued to show a ring pattern when exposed to the fish predator models (Long et al., 1989). Those results are very similar to the results obtained for acoustic habituation in cuttlefish. While both overall response intensity and the number of escape responses decreased over time, total response inhibition was not observed. Cuttlefish often ended test series with a startle or stereotyped startle response, which seemed to be a residual startle response and was often limited to a twitch of the median arms. The continued elicitation of the stereotyped response could indicate that sound is an important source of information for these animals. It may be vital for cuttlefish to keep a certain level of (neural) vigilance when it comes to gathering acoustic information from the environment and continuously processing an auditory scene.

Cephalopod acoustic ecology

Cuttlefish responded to a range of sound levels and frequencies, and response intensity depended on the sounds to which the animals were exposed. Moreover, cuttlefish showed habituation to repeated sound stimuli over time. These findings indicate that cuttlefish, and perhaps cephalopods in general, can use sound as a source of information and have the level of neural development required to process acoustic information from their environment, for example by selecting or learning which sounds can be ‘ignored’ (i.e. habituation to sound). It remains unclear, however, what the function of sound is in the lives of cephalopods, especially in relation to their other well-developed sensory systems, particularly vision. Sound production has been proposed (Iversen and Perkins, 1963) but remains highly speculative. Defense against predators (Hanlon and Budelmann, 1987), prey detection or navigation are possible functions of sound sensitivity because the natural marine soundscape offers a wide range of natural and animal sounds. How invertebrates, in general, use sound is not well understood.

The results herein also provide some indication of sound-induced directional responses by the cuttlefish. While the direction of displacements was not measured explicitly, the animals’ locations in the tank were noted at the time of stimulus presentations. During the habituation experiments, the cuttlefish tended to start testing sessions near the speaker (i.e. a preferred location). At the start of nearly all second sound stimuli, cuttlefish were located higher in the water column and farther from the speaker, suggesting an initial movement away from the sound source. This is in agreement with the earlier indications that the observed responses tended to be avoidance behaviors. From an anatomical perspective, cephalopod statocysts could support directional hearing. Hair cells of the squid and cuttlefish statocyst are polarized and directionally oriented (Budelmann, 1979). Directional response movements have already been proposed in larval invertebrates (Vermeij et al., 2010) but have yet to be shown in adults. The experiments here were not designed to test the directionality of behavioral responses and follow-up examinations would best address such a hypothesis.

Although the sound frequencies and levels used in this study could be produced by natural factors, they are also similar to many anthropogenic noises such as shipping, air guns and drilling (Urick, 1983). Cephalopods may be anatomically impacted by exposure to such sounds, and may even be stranding as a result of intense sound exposures (André et al., 2011). Yet, few detailed behavioral data exist. Behavioral responses may have significant impacts on cephalopod populations, even at lower sound levels or more distant exposures. Measuring the effects of noise from different sources (recordings from shipping or industrial activities, white noise, etc.) on cephalopod behavior and physiology is important to predict how increasing anthropogenic noise in the ocean will affect cephalopod populations and their distribution, key variables because of the importance of cephalopods in marine food webs. Thus, quantifying behavioral responses as well as potential habituation to anthropogenic noise in multiple species could provide a foundation to understanding how cephalopods may respond to noise exposure.

MATERIALS AND METHODS

Experimental overview

Two general experiments were addressed: (1) the frequency range and sound levels that generated a behavioral response and (2) the rate of habituation to pure tones. Animals were free swimming in the center of a 1.08 m diameter

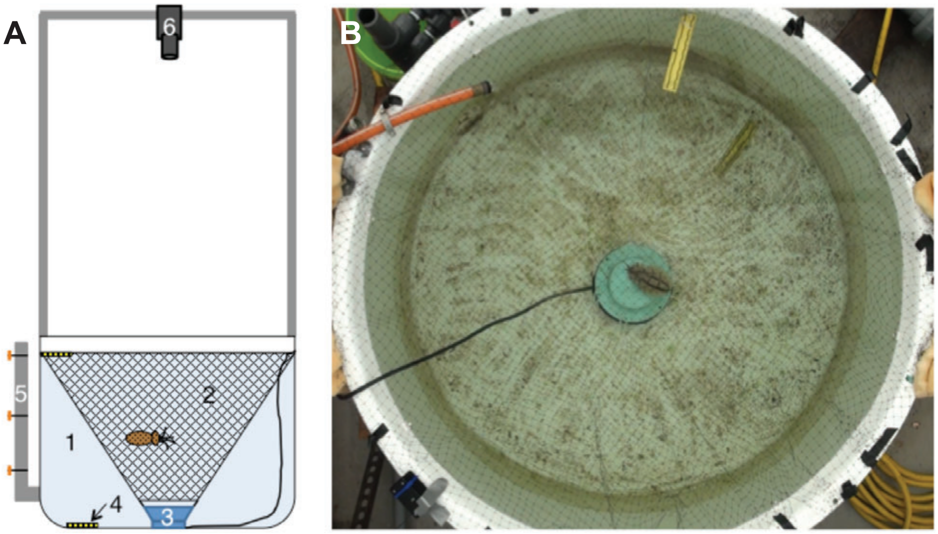

Fig. 7. Experimental set-up. (A) Schematic side view. 1, tank; 2, net; 3, speaker; 4, calibration ruler; 5, outflow pipe; and 6, HD video camera. (B) Detail from a video as recorded by the HD camera above the tank.

tank (Fig. 7). To test the range and level of responses, a matrix of sound stimuli was devised based upon physiological data (Fig. 1), and 10 animals were presented with each sound (a 3 s tone) in a random sequence (with no animal receiving more than four sounds per day). Behavioral responses were recorded using HD video and scored based upon response type (i.e. inking, jetting, startle, color change, fin movement, no response) and responses were plotted relative to stimulus condition. Habituation trials consisted of presenting 10 individual animals with a 3 s tone at 200 Hz every minute for 30 trials. Responses were scored in a similar manner and addressed relative to trial number. Calibrations of sound pressure and particle acceleration were conducted at the beginning and end of the experiments.

Animals

Experiments were conducted between January and July 2012. The 22 cuttlefish used for the experiments were hatched and raised at the Marine Biological Laboratory (MBL) in Woods Hole, MA, USA. Ten animals were used for the first set of experiments addressing frequency range, sensitivity and habituation (January and February): six ‘older’ cuttlefish (~1.5 years old) and four juveniles (~6 months old). This experiment was designed around a matrix that utilized 10 animals at all exposure levels and frequencies (Fig. 1). However, during the first series of experiments, one old cuttlefish and one juvenile died as a result of events unrelated to the tests. They were replaced by new individuals of corresponding age; all animals were included in the analyses (thus, a final N=12 cuttlefish). Based upon these results, tests for frequency range and sensitivity were expanded in July 2012 using 10 additional cuttlefish (1 year old). The older animals were accustomed to being handled for visual experiments but were naive to acoustic tests; the juveniles had never been used for experiments before. During the testing period, the animals were kept at the Woods Hole Oceanographic Institution (WHOI) in Woods Hole. Animals were housed individually in partitioned, shallow tanks with a permanent flow of filtered seawater and were fed defrosted shrimp once a day.

Experimental set-up and protocol

The same basic experimental set-up was used for all tests (Fig. 7). Behavioral response trials took place in a circular fiberglass tank (inner diameter: 1.08 m, depth: 0.60 m), the inside of which was painted white. There was a continuous, low flow of filtered seawater to maintain constant water temperature (14°C) and aerated conditions. Three valves were mounted at different heights on the outflow pipe to allow for regulation of the water level in the experimental tank and partial water changes (in the case of inking, for example). An acoustically transparent black plastic net (2 cm mesh size) was strung in a conical shape from the tank rim to the speaker at the apex. This ensured that the animals swam above the speaker in the water column and prevented them from settling on the bottom of the tank or the speaker, and from touching the side walls of the tank. The speaker was isolated from the tank by two discs of closed-cell neoprene (12.7 mm each) to reduce the potential transmission of vibrations from the speaker to the tank. The tank itself was also isolated from the floor by elevating it on a platform and adding two sheets of open-cell neoprene (12.7 mm each) between the platform and the tank. The netting was loosely hooked to the sides of the tank and hung in a conical fashion, generally encouraging the animals toward the center of the tank, but their location could vary. Because the net only hung loosely and because of the neoprene gaskets, there was little transmission of sound or vibration to the netting or tank. There was no detectable particle motion from these structures into the water column (see calibrations below). Care was taken to ensure animals were in the water column and not touching the sides or netting when we initiated the test tones.

Experimental test tones were produced using a UW30 underwater speaker (Lubell Labs Inc., Columbus, OH, USA). The speaker was connected to a Panasonic CF-52 Toughbook (Bizco Technologies, Lincoln, NE, USA) with a National Instruments 6062E data acquisition card (DAQ, Austin, TX, USA) and running a custom-written program using the National Instruments LabView software. This program allowed us to control the frequency and intensity of the sound and the duration of the sound pulses. A PYLE Chopper Series PLA2210 amplifier (Brooklyn, NY, USA) and a Hewlett-Packard 350D (Palo Alto, CA, USA) attenuator were used to adjust the output from the computer to the speaker. A Tektronix TPS 2014 oscilloscope (Beaverton, OR, USA) was used to visualize the sound pulses and the signal received by the hydrophone during calibration. All tests were video recorded using a Sony HDR-XR550 camera (Tokyo, Japan) placed above the tank and recording at 60 frames s^{-1}.

Sixty-seven different tones, including a silent control, were used to determine the frequency range and sound levels that induced behavioral responses (Fig. 1). These tones lasted 3 s and differed in frequency (80, 100, 150, 200, 250, 300, 400, 500, 700 and 1000 Hz) and intensity (110, 120, 130, 140, 150, 155, 160 and 165 dB re. 1 µPA rms, as calibrated 20 cm away from the speaker). This initial matrix was based on the physiological responses to sound obtained from the longfin squid (Mooney et al., 2010). Based on the behavioral results from the first series of sound tests, an additional set of 10 sound combinations using 700 and 1000 Hz was tested on 10 new animals in July 2012. These animals were housed and tested as described above. At the highest sound levels, some frequencies were distorted as a result of characteristics of the speaker; those sounds were not used for the experiments (blank cells in Fig. 1). Because the animals settled or swam at different distances from the speaker, the received SPLs differed from the calibrated ones. Thus, by changing the speaker output levels (in the range noted above) and as a result of the animal varying its location in the tank (swimming), and thus the distance to the source, the received levels ranged from 85 to 188 dB re. 1 µPa rms (considering all frequencies). Unless stated otherwise, SPL is presented in dB re. 1 µPa rms.

Prior to a sound test, the animal was gently moved from the housing tank to the test tank using a glass container. Before the start of the experiments, the animal was given 1–2 min to settle. All cuttlefish were tested individually and exposed to four different sounds a day (each tone lasted 3 s), but each animal was only exposed once to a specific frequency–sound level combination. The order in which the cuttlefish were tested was randomized every day, with the condition that there should be at least four trials using other individuals between two consecutive tests of one animal, leaving enough time for recovery from handling and exposure to sound. By the end of the testing period (2–3 weeks), the animals had been presented with each sound (66 sounds in total) and the silent control once in a randomized order.

Sound calibrations

Both sound pressure and particle motion were calibrated across the diameter and depth of the tank using the experimental test tones. Calibration measurements were made at the beginning and end of the experiment with essentially the same results. Experimental tones of all tested frequencies were recorded at each location. Sound pressure was measured using a calibrated Reson TC 4014 hydrophone (Slangerup, Denmark). Particle acceleration calculations are described in the next paragraph. For basic SPL (dB re. 1 μPa rms), the hydrophone was suspended 10 cm from the center of the speaker and then moved to the surface in 10 cm steps. This procedure was repeated along the diameter of the tank, with horizontal distance from the speaker increasing in 10 cm increments. The peak-to-peak amplitude of the signals was measured on the oscilloscope, and converted from voltage to SPL using a custom-written script. The tones were concurrently recorded using an Olympus LS-10 PCM pocket recorder (Olympus America Inc., Center Valley, PA, USA).

Particle acceleration values were obtained by measuring the pressure gradient over two closely spaced sound receivers (Gade, 1982). Two custom-made hydrophones (sensitivity: -180 dB re. 1 V μPa^{-1}), vertically spaced 5 cm apart, were fixed in a location 10 cm directly above the speaker. As a stimulus was played, pressure at both hydrophones was concurrently measured (sampling rate: 120 kHz) and digitally stored for later analyses. The hydrophone set-up was moved along the diameter and depth of the tank in 10 cm increments as described for the calibration of the SPL. A total of three depths and 11 positions along the diameter were used and the hydrophones were placed in three different orientations to record sound pressure in all three directions at each measuring point. Particle acceleration (a) was computed from the pressure gradient across the two hydrophones:

$$a = \frac{-\Delta p}{\rho \Delta r}, \tag{1}$$

where Δp is the magnitude of the difference between the waveforms of the two hydrophones, ρ is the density of the medium and r is the distance between the hydrophones (Kalmijn, 1988; Wahlberg et al., 2008). The particle motion was measured in three dimensions by positioning the two hydrophones along three orthogonal axes. The magnitude of the acceleration was computed and used for the data analysis and figures. Comparisons of particle acceleration values for the pressure-derived thresholds were determined by relating the measured pressure at the location with the corresponding particle acceleration at each corresponding location. Within the acoustic near-field of the speaker, the cuttlefish was expected to act as a rigid body with respect to particle acceleration values at each location (Denton and Gray, 1982; Coombs et al., 1992).

From the calibration results, the actual received SPLs and particle acceleration values could be calculated as functions of the distance from the animal to the speaker. Two 15 cm rulers were fixed in the tank: one was placed at the water surface and the other on the bottom of the tank (51 cm from the water surface). A custom-made MatLab tracking program was used to get the coordinates of the rulers, speaker and cuttlefish from the video frames preceding the sound onset. The ratio of the lengths of the two rulers, as observed vertically by the camera, was calculated using their respective pixel lengths in each video. The actual size of each animal (mantle length in mm) was measured and its actual depth could therefore be computed using the sizes of the rulers and the animal's mantle length observed in the videos. Knowing the actual size of the animal, we could compute its expected pixel length at the water surface and compare this with its observed pixel length in each video. The ratio of observed animal length to expected animal length at the surface, compared with the ratio of the ruler lengths, allowed us to calculate the vertical distance from the animal to the speaker. At the time of stimulus presentation, animals were all horizontal, or near-horizontal, in the typical swimming position. The horizontal distance from the speaker to the animal's head (between the eyes) was also determined. Total distance from the speaker to the center of the animal's head (between the eyes) was computed using the horizontal and vertical distances. This total distance was then used to calculate the received SPL and particle acceleration at the animal's head (where the statocysts are located) for each sound test.

SPLs were calibrated at the start of the experiments in January 2012 and again later in July 2012. The calibrations were found to be similar. Accelerations were calibrated once, after all the tests were performed.

Scoring behavior

The behavioral responses for each cuttlefish at each sound combination were categorized using six types of response: no response, body pattern change, fin movements, startle, jetting and inking. Within each type of response, some gradations were defined (Table 1). This scoring system is based on observations of the animals before the experiments and on previous research on the response of cuttlefish to predators and human-elicited stress (Hanlon and Messenger, 1996; Staudinger et al., 2011).

Two behaviors described in Table 1 deserve more extensive explanation: the deimatic pattern and the startle response. The deimatic display is usually observed in experiments involving visual stimuli (Langridge, 2009; Mather, 2010; Staudinger et al., 2011); it is considered a threat (or startle) display to deter potential predators (Staudinger et al., 2013) and is defined by a flattened body shape, paling of the skin, the presence of paired, dark mantle spots, a dark fin line, dark eye rings and a dilation of the pupil (Hanlon and Messenger, 1988; Hanlon and Messenger, 1996). The startle response has been described for several taxa, mostly vertebrates and insects (Hoy et al., 1989; Pilz and Schnitzler, 1996; Koch, 1999; Kastelein et al., 2008) and is provoked by an intense and unexpected stimulus, has a short delay, and involves a fast motor response including escape responses and subtler movement such as eye blinks (Hoy et al., 1989; Koch, 1999; Götz and Janik, 2011). Based on these descriptions of the startle response, we defined one of the responses in *S. officinalis* as a startle response. During the habituation tests (see below), we observed a decrease in startle response intensity and termed this the stereotyped startle response (Table 1). The notion of 'stereotyped' is preferred to 'reflex' in this case because of the lack of neurological investigation.

Habituation to repeated sounds

Two weeks after the initial behavioral responses tests, 10 animals were tested for potential habituation to sound stimuli. Animals were divided into two groups and exposed to repeated 200 Hz, 3 s tones, presented every minute for 30 min. This frequency was chosen because of the general sensitivity and diversity of the responses it elicited in the first series of experiments. Responses to two sound intensities were compared using calibrated sound levels of 150 and 165 dB. Each of the two groups consisted of three old animals and two young ones. The first group started with the sound at 165 dB on the first day and received the 150 dB sound on the second day; the second group got the opposite treatment. As for previous behavioral trials, exposure levels were corrected for the distance of the animal to the speaker. Tests were performed with 30–45 stimuli and behaviors were recorded and scored as noted above. Standard regression analyses were used to estimate the relationship between trial number and rate of occurrence of the different response types.

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Competing interests

The authors declare no competing financial interests.

Author contributions

J.E.S. and T.A.M. designed the experiments, collected the data, and conducted the analyses. S.W.S.G. and R.T.H. assisted with the data analyses and writing the paper.

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Supplementary material

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References

André, M., Solé, M., Lenoir, M., Durfort, M., Quero, C., Mas, A., Lombarte, A., van der Schaar, M., López-Bejar, M., Morell, M. et al. (2011). Low-frequency sounds induce acoustic trauma in cephalopods. *Front. Ecol. Environ.* **9**, 489-493.

Au, W. W. L. and Hastings, M. C. (2009). *Principles of Marine Bioacoustics*. New York, NY: Springer.

Au, W. W. L., Popper, A. N. and Fay, R. J. (2000). *Hearing by Whales and Dolphins*, pp. 512. New York, NY: Springer-Verlag.

Baglioni, S. (1910). Zur kenntnis der leistungen einiger sinnesorgane (gesichtssinn, tastsinn und geruchssinn) und des zentralnervensystems der zephalopoden und fische. *Z. Biol.* **53**, 255-286 (cited in Hanlon and Budelmann, 1987)

Bleckmann, H., Budelmann, B. U. and Bullock, T. H. (1991). Peripheral and central nervous responses evoked by small water movements in a cephalopod. *J. Comp. Physiol. A* **168**, 247-257.

Budelmann, B. U. (1979). Hair cell polarization in the gravity receptor systems of the statocysts of the cephalopods Sepia officinalis and Loligo vulgaris. *Brain Res.* **160**, 261-270.

Budelmann, B. U. (1990). The statocysts of squid. In *Squid as Experimental Animals* (ed. D. L. Gilbert, W. J. Adelman and J. M. Arnold), pp. 421-442. New York, NY: Plenum Press.

Budelmann, B. U. (1992a). Hearing in non-arthropod invertebrates. In *The Evolutionary Biology of Hearing* (ed. D. B. Webster, R. R. Fay and A. N. Popper), pp. 141-155. New York, NY: Springer-Verlag.

Budelmann, B. U. (1992b). Hearing in crustacea. In *The Evolutionary Biology of Hearing* (ed. D. B. Webster, R. R. Fay and A. N. Popper), pp. 131-140. New York, NY: Springer-Verlag.

Budelmann, B. U. and Bleckmann, H. (1988). A lateral line analogue in cephalopods: water waves generate microphonic potentials in the epidermal head lines of *Sepia* and *Lolliguncula*. *J. Comp. Physiol. A* **164**, 1-5.

Cartron, L., Shashar, N., Dickel, L. and Darmaillacq, A.-S. (2013). Effects of stimuli shape and polarization in evoking deimatic patterns in the European cuttlefish, *Sepia officinalis*, under varying turbidity conditions. *Invert. Neurosci.* **13**, 19-26.

Coombs, S., Janssen, J. and Montgomery, J. (1992). Functional and evolutionary implications of peripheral diversity in lateral line systems. In *The Evolutionary Biology of Hearing* (ed. D. B. Webster, R. J. Fay and A. N. Popper), pp. 267-294. New York, NY: Springer-Verlag.

Denton, E. J. and Gray, J. A. B. (1982). The rigidity of fish and patterns of lateral line stimulation. *Nature* **297**, 679-681.

Dijkgraaf, S. (1963). Verusche uber schallwahrnehmung bei tintenfischen. *Naturwissenschaften* **50**, 50.

Fay, R. R. and Popper, A. (1998). *Comparative Hearing: Fish and Amphibians*. New York, NY: Springer.

Fewtrell, J. L. and McCauley, R. D. (2012a). Impact of air gun noise on the behaviour of marine fish and squid. *Mar. Pollut. Bull.* **64**, 984-993.

Finneran, J. J. and Schlundt, C. E. (2011). Subjective loudness level measurements and equal loudness contours in a bottlenose dolphin (*Tursiops truncatus*). *J. Acoust. Soc. Am.* **130**, 3124-3136.

Gade, S. (1982). Sound intensity (Part I. theory). *Brüel & Kjær Technical Review* **3**, 3-39.

Götz, T. and Janik, V. M. (2011). Repeated elicitation of the acoustic startle reflex leads to sensitization in subsequent avoidance behavior and induces fear conditioning. *BMC Neurosci.* **12**, 30.

Hanlon, R. and Budelmann, B. U. (1987). Why cephalopods are probably not 'deaf'. *Am. Nat.* **129**, 312-317.

Hanlon, R. T. and Messenger, J. B. (1988). Adaptive coloration in young cuttlefish (*Sepia officinalis* L.): the morphology and development of body patterns and their relation to behaviour. *Philos. Trans. R. Soc. B* **320**, 437-487.

Hanlon, R. and Messenger, J. B. (1996). *Cephalopod Behaviour*. New York, NY: Cambridge University Press.

Hoy, R., Nolen, T. and Brodfuehrer, P. (1989). The neuroethology of acoustic startle and escape in flying insects. *J. Exp. Biol.* **146**, 287-306.

Iversen, R. T. S. and Perkins, P. J. (1963). An indication of underwater sound production by squid. *Nature* **199**, 250-251.

Kaifu, K., Segawa, S. and Tsuchiya, K. (2007). Behavioral responses to underwater sound in the small benthic octopus *Octopus ocellatus*. *Journal of the Marine Acoustics Society of Japan* **34**, 266-273.

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

Kalmijn, A. D. (1988). Acoustic and hydrodynamic field detection. In *Sensory Biology of Aquatic Animals* (ed. J. Atema, R. R. Fay, A. N. Popper and W. N. Tavolga), pp. 83-131. New York, NY: Springer-Verlag.

Kastelein, R. A., Heul, S., Verboom, W. C., Jennings, N., Veen, J. and de Haan, D. (2008). Startle response of captive North Sea fish species to underwater tones between 0.1 and 64 kHz. *Mar. Environ. Res.* **65**, 369-377.

Kastelein, R. A., Wensveen, P. J., Terhune, J. M. and de Jong, C. A. (2011). Near-threshold equal-loudness contours for harbor seals (Phoca vitulina) derived from reaction times during underwater audiometry: a preliminary study. *J. Acoust. Soc. Am.* **129**, 488-495.

King, A. J. and Adamo, S. A. (2006). The ventilatory, cardiac and behavioural responses of resting cuttlefish (*Sepia officinalis* L.) to sudden visual stimuli. *J. Exp. Biol.* **209**, 1101-1111.

Koch, M. (1999). The neurobiology of startle. *Prog. Neurobiol.* **59**, 107-128.

Komak, S., Boal, J. G., Dickel, L. and Budelmann, B. U. (2005). Behavioural respones of juvenile cuttlefish (*Sepia officinalis*) to local water movements. *Mar. Freshw. Behav. Physiol.* **38**, 117-125.

Langridge, K. V. (2009). Cuttlefish use startle displays, but not against large predators. *Anim. Behav.* **77**, 847-856.

Langridge, K. V., Broom, M. and Osorio, D. (2007). Selective signalling by cuttlefish to predators. *Curr. Biol.* **17**, R1044-R1045.

Long, T. M., Hanlon, R. T., Ter Maat, A. and Pinsker, H. M. (1989). Non-associative learning in the squid *Lolliguncula brevis* (Mollusca, Cephalopoda). *Mar. Behav. Physiol.* **16**, 1-19.

Mann, D. A., Casper, B. M., Boyle, K. S. and Tricas, T. C. (2007). On the attraction of larval fishes to reef sounds. *Mar. Ecol. Prog. Ser.* **338**, 307-310.

Mather, J. A. (2010). Vigilance and antipredator responses of Caribbean reef squid. *Mar. Freshw. Behav. Physiol.* **43**, 357-370.

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. *J. Exp. Biol.* **213**, 3748-3759.

Mooney, T., Hanlon, R. T., Christensen-Dalsgaard, J., Madsen, P. T., Ketten, D. R. and Nachtigall, P. E. (2012). The potential for sound sensitivity in cephalopods. In *The Effects of Noise on Aquatic Life* (ed. A. N. Popper and A. D. Hawkins), pp. 125-128. New York, NY: Springer Science+Business Media, LLC.

Packard, A., Karlsen, H. E. and Sand, O. (1990). Low frequency hearing in cephalopods. *J. Comp. Physiol. A* **166**, 501-505.

Pilz, P. K. D. and Schnitzler, H.-U. (1996). Habituation and sensitization of the acoustic startle response in rats: amplitude, threshold, and latency measures. *Neurobiol. Learn. Mem.* **66**, 67-79.

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

Rankin, C. H., Abrams, T., Barry, R. J., Bhatnagar, S., Clayton, D. F., Colombo, J., Coppola, G., Geyer, M. A., Glanzman, D. L., Marsland, S. et al. (2009). Habituation revisited: an updated and revised description of the behavioral characteristics of habituation. *Neurobiol. Learn. Mem.* **92**, 135-138.

Simpson, S. D., Radford, A. N., Tickle, E. J., Meekan, M. G. and Jeffs, A. G. (2011). Adaptive avoidance of reef noise. *PLoS ONE* **6**, e16625.

Stanley, J. A., Radford, C. A. and Jeffs, A. G. (2010). Induction of settlement in crab megalopae by ambient underwater reef sound. *Behav. Ecol.* **21**, 113-120.

Stanley, J. A., Radford, C. A. and Jeffs, A. G. (2011). Behavioural response thresholds in New Zealand crab megalopae to ambient underwater sound. *PLoS ONE* **6**, e28572.

Stanley, J. A., Radford, C. A. and Jeffs, A. G. (2012). Location, location, location: finding a suitable home among the noise. *Proc. R. Soc. B* **279**, 3622-3631.

Staudinger, M. D., Hanlon, R. T. and Juanes, F. (2011). Primary and secondary defences of squid to cruising and ambush predators: variable tactics and their survival value. *Anim. Behav.* **81**, 585-594.

Staudinger, M. D., Buresch, K. C., Maethger, L. M., Fry, C., McAnulty, S., Ulmer, K. M. and Hanlon, R. T. (2013). Defensive responses of cuttlefish to different teleost predators. *Biol. Bull.* **225**, 161-174.

Stebbins, W. C. (1966). Auditory reaction time and the derivation of equal loudness contours for the monkey. *J. Exp. Anal. Behav.* **9**, 135-142.

Urick, R. J. (1983). *Principles of Underwater Sound.* New York, NY: McGraw-Hill.

Vermeij, M. J. A., Marhaver, K. L., Huijbers, C. M., Nagelkerken, I. and Simpson, S. D. (2010). Coral larvae move toward reef sounds. *PLoS ONE* **5**, e10660.

Wahlberg, M., Schack, H., Wilson, M., Bejder, L. and Madsen, P. T. (2008). Particle acceleration noise generated by boats. *Bioacoustics* **17**, 148-150.

Webster, D. B., Fay, R. R. and Popper, A. N. (1992). *The Evolutionary Biology of Hearing*, pp. 591. New York, NY: Springer-Verlag.