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Behavioral defenses of shellfish prey under ocean acidification

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ABSTRACT Biological interactions between predators and prey constitute a key component of the ecology and evolution of marine systems, and animal behavior can affect the outcome of predator–prey interactions. It has been recently demonstrated that CO2-induced ocean acidification can alter the behavior of marine organisms and potentially alter predator–prey dynamics. This study combines both quantitative (meta-analysis) and qualitative approaches to review the effects of ocean acidification on behavioral prey defenses in marine invertebrates. A systematic literature search identified 34 studies that experimentally assessed behavioral defenses under elevated pCO2, spanning three phyla: crustaceans, echinoderms, and molluscs. A meta-analysis suggested that exposure to elevated seawater pCO2 can negatively affect behavioral defenses in bivalve molluscs and malacostracan crustaceans. By contrast, defenses of cephalopod molluscs seem to be positively impacted by elevated pCO2, whereas gastropods and echinoids appear unaffected. A qualitative assessment of studies on combined effects of ocean acidification and warming revealed that combined effects typically differ from ocean acidification–only effects. Based on a qualitative assessment of three studies to date, neurological interference of GABA_A receptors under elevated pCO2 may play a major role in ocean acidification effects on prey defense behaviors; however, more research is needed, and other mechanistic underpinnings are also important to consider. Ultimately, the results of this study suggest that behavioral prey defenses in some shellfish taxa may be vulnerable to ocean acidification, that the effects of ocean acidification are often different under warming scenarios than under present-day temperature scenarios, and that GABA_A interference may be an important mechanism underpinning behavioral responses of shellfish prey under ocean acidification. Despite the importance of shellfish behavioral defenses in the ecology and evolution of marine biological communities, however, research to date has only scraped the surface in understanding ocean acidification effects. Increased research efforts on the effects of multiple stressors, acclimation and adaptation, environmental variability, and complex situational and ecological contexts are needed. Studies of fish behavioral defenses under ocean acidification can help streamline hypotheses and experimental approaches, particularly given the similar effects of elevated pCO2 on GABA_A function.

KEY WORDS: cognition, environmental stress, GABA, invertebrates, pH, temperature

INTRODUCTION

Interactions between predators and their prey constitute an integral part of the ecology and evolution of marine organisms, as well as the structure and function of biological communities. In his pioneering work, Connell (1961) documented that the distribution and competitive ability of rocky intertidal barnacles were controlled by the predatory behavior of coexisting whelks. Soon after, Bob Paine demonstrated that the removal of predatory sea stars along the rocky intertidal shores of Washington resulted in less predation on mussels and an extraordinary community transformation (Paine 1966, Paine & Schindler 2002). Since those early studies in rocky intertidal systems, studies have documented the importance of predator–prey interactions in the structure and function of a wealth of marine systems, including pelagic ecosystems (Heithaus et al. 2008), mudflats (Reise 1977, Peterson 1982, Munroe et al. 2015), salt marshes (Silliman & Bertness 2002, Silliman et al. 2005), subtidal reefs (Barkai & McQuaid 1988), and seagrass beds (Heck & Thoman 1981, Orth et al. 1984). Predator–prey interactions are also known to play an important role in marine bioinvasions (Rilov 2016). Given their widespread and influential role in marine systems, understanding predator–prey interactions in the past, present, and future is critical to understanding biodiversity and ecosystem functioning.

Animal behavior is an important component of predator–prey relationships, resulting in a broad literature describing the behavioral responses of prey. For example, personality (Briffa 2013, Belgrad & Griffen 2016), activity and locomotion (Richardson 2001, Sweeney et al. 2013), avoidance behaviors (Cotton et al. 2004), and the use of shelters, burrows, and other refugia (Mima et al. 2003, Hemmi & Merkle 2009, Alcaraz & Arce 2017) can all influence the propensity of an individual or group of organisms to be preyed on. Such alterations in predation potential can have implications for the success and fitness of a given prey species (and the corresponding success and fitness of the predator). It is thus important to consider the behavioral defenses of prey species to predation when assessing predator–prey interactions and associated ecological outcomes.

Behavioral defenses of shellfish prey can be affected by the physical environment. For example, temperature has been documented to affect individual boldness of the hermit crab Pagurus bernhardus (Briffa et al. 2013) and the burrowing behavior of the softshell clam Mya arenaria (Clements et al. 2017). Similarly, hypoxia has been documented to reduce the burrowing capacity of the infaunal clam Macoma balthica (Tallqvist 2001). Consequently, behavioral prey defenses (along with a swath of other behaviors) are vulnerable to a changing marine environment (Wong & Candolin 2015), and behavioral alterations brought about by environmental change in the global ocean have the potential to influence entire marine ecosystems (Nagelkerken & Munday 2016).
One marine global change stressor that has received much attention over the past 15 y is ocean acidification—the alteration of seawater carbonate chemistry resulting from the absorption of excess atmospheric CO₂ by the oceans (Doney et al. 2009, Hoegh-Guldberg et al. 2014). Research investigating the impacts of ocean acidification on marine life has primarily focused on calcifying marine organisms, in large part because of the anticipated vulnerability of the calcification process to changes in seawater pH (Orr et al. 2005, Ries et al. 2009, Kroeker et al. 2010, 2013). Recent evidence, however, suggests that ocean acidification can also have drastic effects on the behavior of marine organisms (see reviews by Briffa et al. 2012, Clements & Hunt 2015). Thus, although the vulnerability of morphological defenses such as shell has been relatively well studied, less is known of the impacts of ocean acidification on shellfish behavioral defenses (see Fig. 2 in Kroeker et al. 2014).

In this article, the current literature regarding ocean acidification effects on invertebrate defense behaviors was quantitatively and qualitatively reviewed to provide an overview of ocean acidification effects on behavioral prey defenses in marine shellfish. Specifically, a meta-analysis of ocean acidification effects on prey defense behaviors was conducted from studies to date. In addition, available studies were qualitatively reviewed to assess interactive effects of ocean acidification and warming on shellfish behavioral defenses, and to highlight a potential biological mechanism responsible for observed effects (GABA neural interference). Knowledge gaps are also discussed, and key considerations for future research are provided.

LITERATURE SEARCH AND DATA COLLECTION

A systematic online keyword search was conducted in Scopus and Google Scholar to obtain relevant studies (peer-reviewed articles and graduate theses) using various combinations of specific keywords: “ocean acidification” or “acidification” or “carbon dioxide” or “CO₂,” combined with “behavior” and/or “predator” and/or “defense” and/or “behavioral defense” and/or “predator-prey” and/or “avoidance” and/or “escape.” Only original research articles that directly measured prey defense behavior on a species of shellfish (molluscs, arthropods, and echinoderms) were archived for analysis. The reference lists and citations of each relevant article were subsequently checked to obtain any additional articles that may have been missed using the online keyword search.

From each article, qualitative and quantitative attributes were extracted: (1) bibliographical information; (2) study species and associated taxonomic information; (3) life stage of the organism(s) tested; (4) the climatic region where study animals were collected (based on the geographic location of animal collection and/or experimentation stated); (5) seawater conditions (temperature, salinity, pH, and pCO₂ when available), exposure time (i.e., duration of exposure to pCO₂ treatments), the prey defense behavior measured, whether a predator cue was present when the behavior was measured, and the statistical effect and associated functional effect (“function” was defined in relation to avoiding or escaping a predation event; for example, an increase in self-righting time would be interpreted as functionally negative (and vice versa), and a decrease in reaction time would be functionally positive (and vice versa)). For pH and pCO₂ conditions, the magnitude of change (i.e., offset) was calculated for each experimental treatment by subtracting the mean of the control from that of each experimental treatment; all treatments considered were static (i.e., experimental pH and pCO₂ conditions were kept stable during experimental exposures). Where possible, unavailable pCO₂ values were estimated in CO2SYS (Pierrot et al. 2006) using the published temperature, salinity, and pH values of the treatments along with a total alkalinity value of 2,345 µatn (WHOI 2012, using the first and second dissociation constants of Mehrbach et al. (1973) refit by Dickson and Millero (1987). For each article relevant to the meta-analysis, the mean, SD, and sample size for each treatment group were recorded; if multiple behaviors or experiments were measured in the same study, each was considered as an individual data point (i.e., multiple data points from the same study were included). The data were collected from either raw data supplied as supplementary information or from published tables and figures in the main article; data from figures were estimated using ImageJ (Schneider et al. 2012).

META-ANALYSIS OF OCEAN ACIDIFICATION EFFECTS ON PREY DEFENSE BEHAVIORS: METHODOLOGY

Deriving Individual Effect Sizes

To derive a quantitative understanding of ocean acidification effects on shellfish behavioral defenses, a meta-analysis was conducted. The effect size used was the natural logarithm-transformed response ratio (lnRR), which is defined as

\[ \ln RR = \ln \left( \frac{X_E}{X_C} \right) \]

where \( X_E \) and \( X_C \) are the average measured response in the experimental and control treatments, respectively. This effect size metric has a high capacity to detect true effects, is robust to low sample sizes, and quantifies the proportional change in a response variable due to experimental manipulations (Lajeunesse & Forbes 2003). It is important to note that, for some behaviors, an increase in the behavioral measurement corresponds to a negative functional response (but would result in a positive effect size estimate). In such instances, the directionality of the calculated effect size was inverted (i.e., positive values were changed to negative ones, and vice versa) to adequately reflect the functional consequence of the behavioral change.

Effect size variance was calculated as

\[ \nu = \frac{(S_E)^2}{n_EX_E^2} + \frac{(S_C)^2}{n_CX_C^2}, \]

where \( S \) and \( n \) are the SD and sample size, respectively, for a given experimental treatment (denoted by the subscripts \( C \) [control] and \( E \) [experimental, i.e., elevated pCO₂]); \( X_E \) and \( X_C \) are defined as aforementioned. Thus, studies with greater replication and less-variable responses were considered to be more precise estimates of a population effect and, as such, were weighted more heavily when calculating mean effect sizes (Hedges & Olkin 1985). This approach provides a conservative estimate of the mean effect size and increases the confidence that a statistically significant effect size is a true effect.

Determining Drivers of Individual Effect Sizes

Rather than assessing effect sizes between a priori defined groups, Akaike’s information criterion (AIC) model selection was used to determine parameters that best accounted for the observed variability in effect sizes, and effect sizes were assessed...
across levels within each contributing parameter identified by AIC. Linear mixed models with additive fixed factors (i.e., interactions were not tested) were built for all possible combinations of predictor variables. Categorical predictor variables included in the models were taxonomy (phylum and class), climatic region (temperate, tropical, or polar; if animals were from the deep sea, they were considered in a separate group), and life stage (larvae, juvenile, or adult); study was included as a random variable to account for nonindependence due to the incorporation of multiple effect sizes from a single study. Before analysis, correlations between effect size and three continuous variables—exposure time, sample size, and pCO₂ offset (experimental–control pCO₂) —were also explored. There was a significant correlation between effect size and pCO₂ offset ($r = -0.66, P < 0.001$; Fig. 1), but not exposure time ($r = -0.11, P = 0.377$) or sample size ($r = 0.16, P = 0.219$); therefore, pCO₂ offset, but not exposure time or sample size, was included in the AIC models as a continuous predictor variable. Predictor variables were not significantly correlated ($r < 0.36$ for all pairwise correlations) with the exception of phylum and class ($r = 0.93$); therefore, models including both phylum and class as predictor variables were excluded from AIC selection. A “null” model (i.e., model with no fixed predictor variables and only a random factor of measurement nested within study) was also included in AIC selection. This resulted in a total of 24 additive models.

Model selection was based on AIC and log likelihood values (Burnham & Anderson 2002; lowest AIC and highest log likelihood values indicate the “best” model), and all models with a delta AIC ($\Delta$ AIC) $\leq 2$ were considered as “best” models (Burnham & Anderson, 2002). The AIC model selection was conducted on all studies, as well as only those with a pCO₂ offset consistent with near-future projections ($<1,000$ μatm), to determine whether predictors of effect size differed when pCO₂ projections beyond near-future were included versus excluded.

**Effect Size Analysis of Predictor-Level Responses**

Once the “best” model was defined, the mean lnRR and 95% confidence interval (CI) for each level of the predictor variable(s) that were present in the best model were calculated. To provide conservative estimates of effect size variance, bootstrapped (10,000 replicates), bias-corrected, and accelerated (BCa) 95% CIs were used (Adams et al. 1997). Mean effect sizes were estimated using weighted random effect models, which weight individual effect sizes by the inverse of the effect size variance (Hedges & Olkin 1985). Random effects models were used as opposed to fixed effects models because of inherent differences in conditions between studies (i.e., species and geographic location). To account for nonindependence associated with using multiple data points per study, mean effect sizes were calculated using three-level meta-analytical models (Nakagawa et al. 2015; Noble et al. 2017), including “measure nested within study” as a random variable. Mean lnRR and associated variance (bootstrapped BCa 95% CIs) were only derived for factor levels with $n \geq 3$.

Statistical significance was determined by assessing whether the BCa 95% CI surrounding a mean effect size overlapped with 0 (Lajeunesse & Forbes 2003). Heterogeneity in effect sizes for each level of the factors identified in the top candidate model(s) was tested using Q-tests of heterogeneity (Lajeunesse & Forbes 2003). Given the significant correlation between effect size and pCO₂ offset for all pCO₂ conditions ($r = -0.66, P < 0.001$), but the lack of correlation for near-future only ($r = -0.28, P = 0.075$), two separate analyses were conducted: one for all pCO₂ conditions and another for only near-future pCO₂ conditions (i.e., pCO₂ offset $<1,000$ μatm; upper estimate for average pCO₂ increase based on the IPCC RCP8.5 projection for 2100). A null effect was signified when lnRR $= 0$, whereas negative and positive effects were defined by negative and positive lnRR values, respectively (Hedges et al. 1999).

**Sensitivity Analysis and Publication Bias**

The influence of single studies that elicited unusually large effect sizes was investigated using sensitivity analysis. Herein, observations within each level of the factors present in the best AIC model were systematically ranked according to their observed mean effect size; the largest effect size was then removed from the dataset, and the analysis was rerun. The relative contribution of individual studies to the observed mean effect sizes was also considered; however, no single study contributed more than four experiments to the meta-analysis (three studies contained four experiments, whereas many other studies contained three experiments) and, as such, the data were not reanalyzed excluding studies that contributed multiple observations to the overall effect size. To test for publication bias, the number of studies with an lnRR $= 0$ that would be required to change a significant effect size response to a nonsignificant response was determined using Rosenthal’s fail-safe number (Rosenthal 1979). The analysis for a given category was considered robust if Rosenthal’s fail-safe number was $\geq 5$ (Kroeker et al. 2010, 2013; Harvey et al. 2013).

**Analytical Details**

All analyses were conducted in R v. 3.4.1 (R Core Team 2017) with a significance threshold of $\alpha = 0.05$. Effect size analyses were conducted using the metafor package (Viechtbauer 2010, 2017), with 95% BCa CIs generated using the “boot” package (Canty & Ripley 2017). Pearson correlations were tested using the rcorr function in the Hmisc package (Harrell Jr. 2017), AIC model selection analysis was conducted using the
AICcmodavg package (Mazerolle 2017), and $R^2$ values for linear mixed models were computed using the MuMIn package (Bartoň 2018). Before analyses including individual effect sizes (i.e., Pearson correlations and AIC), effect sizes were transformed (ln+10) to achieve normality.

QUALITATIVE ASSESSMENTS OF OCEAN ACIDIFICATION–WARMING EFFECTS, AND THE ROLE OF GABA$\alpha$; METHODOLOGY

In addition to the meta-analysis of ocean acidification effects on prey defense behaviors, a qualitative review was also used to assess the effects of ocean acidification in the context of warming and to assess the role of GABA$\alpha$ interference in driving elevated $p$CO$_2$ effects on shellfish prey defense behaviors. Qualitative assessments were used for these two topics because of the low number of relevant studies ($n=7$ for acidification–warming and $n=3$ for GABA$\alpha$). These assessments consisted of a vote counting approach, whereby the number of studies lending evidence for or against a certain hypothesis was used to determine the likelihood of a particular outcome. For acidification–warming studies, the percentage of articles that showed statistical difference between the acidification-only and acidification–warming groups was computed. Similarly, for GABA$\alpha$ studies, the percentage of articles that suggested GABA$\alpha$ interference may be the driving mechanism of ocean acidification effects on behavior was calculated. It is important to note here that this approach is not quantitatively rigorous and therefore has less inferential power than the meta-analysis in the previous section; however, such an exercise can highlight potential trends and provide directions for future studies in these areas.

AN OVERVIEW OF THE STUDIES

The literature search uncovered 34 studies (peer-reviewed articles and graduate theses), assessing the effects of elevated $p$CO$_2$ on shellfish prey defense behaviors (Table 1). Of those, 28 were used in the meta-analysis of ocean acidification effects on defense behaviors (meta-analysis only included studies where the mean, variance, and sample size for each treatment were obtainable). The first study to directly assess ocean acidification effects on prey defense behavior was published by Bibby et al. (2007), who measured predator avoidance behavior in the intertidal gastropod Littorina littorea. Therein, snails increased the avoidance behavior in response to predatory crabs as a compensatory defense, as ocean acidification hindered the primary defense of snails—shell thickening. In subsequent years, studies neglected assessments of shellfish behavioral defenses until 2011 when three more studies were published (Fig. 2A). Thereafter, studies of ocean acidification effects on shellfish prey behavior became more popular, peaking in 2014. Since 2011, at least one study assessing ocean acidification effects on shellfish prey defenses has been conducted per annum (Fig. 2A).

The studies obtained in the literature search encompassed three phyla—molluscs ($n=23$, 68%), arthropods ($n=5$, 15%), and echinoderms ($n=7$, 20%) (Fig. 2B; total number of studies $>34$ and total percentage $>100\%$ because of a single study that assessed both a gastropod and an arthropod). Molluscan studies spanned three taxonomic classes and included studies on bivalves ($n=7$, 20% of all studies), cephalopods ($n=3$, 9% of all studies), and gastropods ($n=13$, 37% of all studies) (Fig. 2B). Echinoderm studies and crustacean studies were exclusively restricted to the classes Echinoidea and Malacostraca, respectively. Studies on bivalves, gastropods, and echinoids spanned across the larval, juvenile, and adult life stages of these organisms, whereas studies on juvenile cephalopods were absent, and studies on malacostracan crustaceans have been restricted to adults (Fig. 2B). A total of 19 studies assessed the effect of ocean acidification on the behavioral defenses of adult prey, whereas five and six studies tested such effects in juveniles and larvae, respectively (see Fig. 1B for life stage percentages for each taxonomic class). Importantly, only 15% of the studies ($n=5$ of 34) included predator cues in their experiments testing for effects of ocean acidification on prey defense behaviors. Thus, most behaviors, although relevant to prey defense, were measured in the absence of predator cues.

Seven studies reported strictly negative (i.e., all experiments finding a significant negative effect of ocean acidification) functional effects of ocean acidification on behavioral prey defenses ($n=5$ bivalve + 2 gastropod studies), whereas four studies reported strictly positive effects ($n=2$ cephalopod + 2 gastropod studies) (Fig. 2B). Null responses to ocean acidification were observed in 15 studies; $n=6$ gastropod + 6 echinoderm + 3 malacostracan studies) (Fig. 2B). Six studies on molluscan taxa reported mixed responses to ocean acidification ($n=2$ bivalve + 1 cephalopod + 3 gastropod studies) (Fig. 2B).

A META-ANALYSIS OF OCEAN ACIDIFICATION EFFECTS ON SHELLFISH BEHAVIORAL DEFENSES

Meta-Analysis Results

Effects of ocean acidification on shellfish behavioral defenses were predominantly driven by $p$CO$_2$ offset, taxa, and life stage. When all $p$CO$_2$ conditions were considered, AIC model selection revealed the model including $p$CO$_2$ offset + class + life stage as the “best” model (Table 2). This model explained 59% ($R^2=0.59$) of the variance in individual effect sizes. A second model including $p$CO$_2$ offset + life stage could not be excluded (delta AIC = 1.75) and explained 58% ($R^2=0.58$). When only near-future $p$CO$_2$ anomalies where considered, a number of candidate models (i.e., those with a delta AIC <2) were evident; these included the model including $p$CO$_2$ offset, the model including class, the model including life stage, and the null model. Of these models, the model including class explained the most variation ($R^2=0.30$), followed by life stage ($R^2=0.23$), the null model ($R^2=0.22$), and $p$CO$_2$ offset ($R^2=0.20$). For both $p$CO$_2$ groupings, effect size was negatively related to $p$CO$_2$ offset, although the relationship for near-future $p$CO$_2$ values was weak and non-significant (Fig. 1). Given that the fixed factors of class and life stage appeared in the best models, the effect size analysis was restricted to testing for ocean acidification effects on prey defense behaviors across classes and life stages. It is important to note, however, that the $R^2$ values for all $p$CO$_2$ conditions were primarily explained by $p$CO$_2$ offset and that those for near-future $p$CO$_2$ only were relatively low. This suggests that the predictive power of class and life stage was relatively low; nonetheless, they appeared to be more important in explaining the effect size variation than other factors based on AIC model selection.

When all $p$CO$_2$ offsets were included, meta-analysis revealed that mean effect sizes of bivalve and malacostracan defenses were significantly lower than zero (Fig. 3A). By contrast, the mean effect size in cephalopods was significantly higher than zero, despite substantial variability (Fig. 3A). Effect sizes in both
TABLE 1.
Summary of experimental studies assessing the effects of elevated $p$CO$_2$ on the behavioral prey defenses.

| Reference                          | Species                      | Climatic region | Life stage | Acclim. time | Behavioral metric                        | Predator cue? | pH       | $p$CO$_2$ | Functional response |
|------------------------------------|------------------------------|-----------------|------------|--------------|------------------------------------------|---------------|----------|-----------|---------------------|
| Schalkhausser et al. (2013)        | *Pecten maximus*             | Temperate       | Adult      | 30           | Number of claps                          | No            | 8.19     | 7.76      | -0.43               | Null                |
|                                    |                              |                 |            |              | Clapping force                           |               | 395      | 1,086     | 691                  |                     |
|                                    |                              |                 |            |              |                                          |               | n.r      | n.r       | n.r                  | Negative            |
| Green et al. (2013)*               | *Mercenaria mercenaria*      | Temperate       | Larvae     | 0            | Percent burrowed                         | No            | n.r      | n.r       | n.r                  | Negative            |
| Clements & Hunt (2014*)            | *Mya arenaria*               | Temperate       | Juvenile   | 0            | Percent burrowed                         | No            | n.r      | n.r       | n.r                  | Negative            |
| Rodrigoz-Romero et al. (2014)      | *Ruditape s philippinarum*   | Tropical        | Adult      | 10           | Percent burrowed                         | No            | 7.93     | 7.07      | -0.86               | Negative            |
|                                    |                              |                 |            |              |                                          |               | 392      | 4,880     | 4,488                |                     |
| Clements et al. (2016)*            | *M. arenaria*                | Temperate       | Juvenile   | 0            | Percent burrowed                         | No            | 7.26     | 6.50      | -0.76               | Negative            |
| Clements et al. (2017)             | *M. arenaria*                | Temperate       | Juvenile   | 0            | Percent burrowed                         | No            | 8.08     | 7.74      | -0.34               | Negative            |
| Peng et al. (2017)                 | *Sinonovacula constricta*    | Tropical        | Adult      | 7            | Burrowing depth                          | No            | 7.57     | 7.22      | -0.86               | Negative            |
|                                    |                              |                 |            |              |                                          |               | 7.22     | 2,859     | 2,508                |                     |
| Cephalopoda                        |                              |                 |            |              |                                          |               | 6.63     | 21,833    | 21,441               | Negative            |
|                                    |                              |                 |            |              |                                          |               | 6.14     | 106,029   | 105,637              |                     |
| Spady et al. (2014)                | *Idiosepius pygmaeus*        | Tropical        | Adult      | 5            | Mean number line Crosses                 | No            | 8.13     | 7.99      | -0.14               | Positive            |
|                                    |                              |                 |            |              | Percent high activity                    |               | 447      | 626       | 179                  | Positive            |
|                                    |                              |                 |            |              |                                          |               | 7.83     | 956       | 509                  | Positive            |
|                                    |                              |                 |            |              | Percent inking                           |               | 7.99     | 7.71      | -0.28               | Positive            |
|                                    |                              |                 |            |              |                                          |               | 8.00     | 435       | 935                  | Positive            |
|                                    |                              |                 |            |              | Percent defense posture versus jetting   |               | 7.99     | 7.71      | -0.28               | Positive            |
|                                    |                              |                 |            |              | Percent display type                     |               | 7.99     | 7.71      | -0.28               | Positive            |
|                                    |                              |                 |            |              |                                          |               | n/a      | n/a       | n/a                  | Positive            |
|                                    |                              |                 |            |              |                                          |               | n/a      | n/a       | n/a                  | Positive            |
| Spady et al. (2018)                | *Sepioteuthis lessonia*      | Tropical        | Adult      | 28           | Distance moved                           | No            | 7.99     | 7.71      | -0.28               | Positive            |
|                                    |                              |                 |            |              | Speed                                    |               | 435      | 935       | 500                  | Positive            |
|                                    |                              |                 |            |              |                                          |               | 7.99     | 7.71      | -0.28               | Positive            |
|                                    |                              |                 |            |              | Percent time active                      | No            | 7.99     | 7.71      | -0.28               | Positive            |
|                                    |                              |                 |            |              |                                          |               | 7.99     | 7.71      | -0.28               | Positive            |
|                                    |                              |                 |            |              |                                          |               | n/a      | n/a       | n/a                  | Positive            |
| Zakroff et al. (2018)*             | *Doryteuthis pealeii*        | Temperate       | Larvae     | 0            | Time spent in area                        | No            | 8.00     | 7.88      | -0.12               | Null                |
|                                    |                              |                 |            |              |                                          |               | 400      | 550       | 150                  | Null                |
|                                    |                              |                 |            |              |                                          |               | 7.66     | 850       | 450                  | Null                |
|                                    |                              |                 |            |              |                                          |               | 7.54     | 1,300     | 900                  | Null                |
|                                    |                              |                 |            |              |                                          |               | 7.55     | 1,500     | 1,100                | Null                |
|                                    |                              |                 |            |              |                                          |               | 7.48     | 1,700     | 1,300                | Null                |
|                                    |                              |                 |            |              |                                          |               | 7.37     | 1,900     | 1,500                | Negative            |
|                                    |                              |                 |            |              |                                          |               | 7.40     | 2,200     | 1,800                | Negative            |

continued on next page
| Reference                  | Species                               | Climatic region | Life stage | Acclim. time | Behavioral metric               | pH Control | pH Exp | pH Offset | pCO₂ Control | pCO₂ Exp | pCO₂ Offset | Functional response |
|----------------------------|---------------------------------------|-----------------|------------|--------------|---------------------------------|------------|--------|-----------|---------------|----------|-------------|---------------------|
| Gastropoda                 |                                       |                 |            |              |                                 |            |        |           |               |          |             |                     |
| Bibby et al. (2007)        | *Littorina littorea*                  | Temperate       | Adult      | 15           | Speed                           | 8.00       | 7.70   | -0.30     | 400           | 1,000   | 600         | Null                |
| Fields (2013)              | *Conomurex lhuuanus*                  | Tropical        | n.r        | 10           | Speed                           | 7.97       | 6.63   | 1.34      | 507           | 5,382   | 4,875       | Positive            |
| Manriquez et al. (2013)    | *Concholepas concholepas*             | Tropical        | Juvenile   | 83           | Speed                           | 8.03       | 7.80   | -0.23     | 388           | 716     | 328         | Negative            |
| Manriquez et al. (2014)    | *Concholepas concholepas*             | Tropical        | Larvae     | 150          | Speed                           | 8.05       | 7.65   | 0.39      | 388           | 1,036   | 648         | Negative            |
| Schram et al. (2014)       | *Nacella concinna*                    | Polar           | Adult      | 42           | Speed                           | 8.11       | 7.81   | 0.30      | 371           | 994     | 623         | Negative            |
| Margarella antarctica     |                                       | Polar           | Adult      | 42           | Speed                           | 8.05       | 7.65   | 0.39      | 388           | 1,036   | 648         | Negative            |
| Quieros et al. (2014)      | *Nucella lapillus*                    | Temperate       | Adult      | 425          | Speed                           | 8.03       | 7.93   | 0.10      | 541           | 689     | 148         | Negative            |
| Watson et al. (2014)       | *Gibberulus gibberulus* gibbonus     | Tropical        | Adult      | 5            | Number of jumps                 | 8.17       | 7.85   | 0.32      | 405           | 961     | 556         | Negative            |
| Zhang et al. (2014)        | *Reticuassa festiva*                  | Tropical        | Larvae     | 1            | Swimming speed                  | 8.05       | 7.75   | 0.30      | 366           | 865     | 499         | Null                |
| Jellison et al. (2016)*    | *Tegula funebralis*                   | Tropical        | Adult      | 5            | Path length                     | n.r        | n.r    | n.r       | Null          | Null    | Null        | Negative            |
| Manriquez et al. (2016)    | *Concholepas concholepas*             | Tropical        | Juvenile   | 90           | Percent time out of water       | 7.85       | 7.47   | 0.38      | 539           | 1,463   | 924         | Positive            |
| Domenici et al. (2017)     | *Concholepas concholepas*             | Tropical        | Juvenile   | 180          | Self-righting time              | 7.85       | 7.47   | 0.38      | 539           | 1,463   | 924         | Null                |
| Watson et al. (2017)       | *Conus marmoreus*                     | Tropical        | Adult      | 14           | Speed                           | 8.19       | 7.86   | 0.33      | 388           | 975     | 587         | Positive            |

continued on next page
| Reference          | Species                           | Clastic region | Life stage | Acclim. time | Behavioral metric                  | Predator cue? | pH | pCO2  | Functional response |
|--------------------|----------------------------------|----------------|------------|--------------|------------------------------------|---------------|----|-------|-------------------|
| Walsh (2018)       | Tritia obsoleta                  | Temperate      | Adult      | 0            | Time buried                        | No            | 6.98 | 6.51  | -0.47            | Negative          |
| Echinoidea         |                                  |                |            |              | Self-righting time                 |               |     |       |                   |                  |
|                    |                                  |                |            |              | Left-right preference              |               |     |       |                   |                  |
|                    |                                  |                |            |              | Percent burrowed                   | No            |     |       |                   |                  |
| Chan et al. (2011) | Dendraster excentricus           | Temperate      | Larvae     | 10           | Speed                              | No            | n.r | n.r   | n.r              | Null              |
|                    |                                  |                |            |              | Helical pitch                      |               |     |       |                   |                  |
| Hatfield-Vaughan   | Mesocentrotus franciscanus       | Temperate      | Juvenile   | 154          | Percent avoidance                  | Yes           | 7.96 | 7.68  | -0.28            | Null              |
| Barry et al. (2014)| Strongylocentrotus fragilis     | Tropical (deep sea) | Adult      | 27           | Speed                              | No            | 7.55 | 7.14  | -0.41            | Null              |
| Chan et al. (2015) | Strongylocentrotus droebachiensis | Temperate     | Larvae     | 14           | Speed                              | No            | 8.04 | 7.68  | -0.36            | Null              |
| Chan et al. (2016) | Anphiura filiformis              | Temperate      | Larvae     | 13           | Speed                              | No            | 8.05 | 7.67  | -0.38            | Null              |
|                    | Strongylocentrotus purpuratus    | Temperate      | Larvae     | 29           | Speed                              | No            | 8.03 | 7.69  | -0.34            | Null              |
|                    |                                  |                |            |              |                                    |               |     |       |                   |                  |
| Malacostraca       | Pagurus bernhardus               | Temperate      | Adult      | 5            | Latency of shell change            | No            | 8.22 | 6.85  | -1.37            | Negative          |
| de la Haye et al.  |                                  |                |            |              | Antennular flicking                |               |     |       |                   |                  |
|                    |                                  |                |            |              | Movement duration                  |               |     |       |                   |                  |
|                    |                                  |                |            |              |                                    |               |     |       |                   |                  |
| Alenius & Munguia  | Paradella dianae                 | Tropical       | Adult      | 21           | Percent time swimming              | No            | 8.17 | 7.60  | -0.57            | Negative          |
| (2012)             |                                  |                |            |              |                                    |               |     |       |                   |                  |
| de la Haye et al.  | P. bernhardus                    | Temperate      | Adult      | 5            | Antennular flicking                | No            | 8.21 | 6.81  | -1.40            | Negative          |
| (2012)             |                                  |                |            |              | Movement duration                  |               |     |       |                   |                  |
| Zittier et al. (2013) | Hyas araneus                  | Polar          | Adult      | 12           | Self-righting time                 | No            | 8.08 | 7.74  | -0.34            | Null              |
|                    |                                  |                |            |              |                                    |               |     |       |                   |                  |
|                    |                                  |                |            |              |                                    |               |     |       |                   |                  |
| Kim & Barry (2016) | Pagurus tanneri                  | Tropical (deep sea) | n.r        | 28           | Emergence time                     | No            | 7.60 | 7.12  | -0.48            | Null              |
|                    |                                  |                |            |              |                                    |               |     |       |                   |                  |
| Rankin (2017)      | Pelia tumida                     | Tropical       | Adult      | 35           | Percent decoration                 | No            | 7.99 | 7.75  | -0.24            | Null              |
| Walsh (2018)       | Corophium concholepas volutator  | Temperate      | Adult      | 0            | Percent burrowed                   | No            | 6.98 | 6.51  | -0.47            | Negative          |

*Studies not included in the meta-analysis because of lack of data availability. Studies are ordered chronologically within each respective taxonomic class. n.r, not reported; n/a, not applicable; Acclim., acclimation; Exp., experimental; Anom., offset. Acclimation time is reported in days, and pCO2 is reported in µatm.
gastropods and echinoids were not significantly different from zero (Fig. 3A). Sensitivity analysis revealed that unusually large effect sizes did not influence the statistical outcome of class effect sizes (data not shown). The categorical analysis was robust (Rosenthal’s fail-safe >7) for all classes, except for echinoids [Table 3; Rosenthal’s fail-safe = 0, which was unsurprising given that all studies on echinoids reported exclusively null statistical effects (Fig. 2B)]. The significant negative effect size for bivalves was retained when only near-future pCO2 conditions were considered (Fig. 3B). Likewise, the significant positive effect size for cephalopods remained when only near-future conditions were considered, along with the null effect size for gastropods and echinoids (Fig. 3B).

In contrast to when all pCO2 conditions were considered, the effect size for malacostracan crustaceans was not significantly different from zero (Fig. 3B) and the robustness of the malacostracan effect was reduced when only near-future conditions were considered (Table 3; Rosenthal’s fail-safe number = 2). Heterogeneity (Q-statistic) for all classes was significant for both pCO2 groupings (Table 3).

With respect to life stage, the meta-analysis revealed that only juvenile effect sizes were significantly lower than zero (Fig. 4). This was true for all pCO2 conditions and near-future conditions only. The mean effect size for both larvae and adults was not significantly different from zero for both pCO2

| Model | K | AICc | ΔAIC | AICc Wt | Cum Wt | LL | $R^2$ |
|-------|---|------|------|--------|--------|----|------|
| All pCO2 | | | | | | | |
| Class + life stage + pCO2 offset | 10 | 144.29 | 0.00 | 0.40 | 0.40 | −60.03 | 0.59 |
| Life stage + pCO2 offset | 6 | 145.88 | 1.59 | 0.18 | 0.59 | −66.19 | 0.58 |
| Near-future pCO2 only | | | | | | | |
| Null model | 4 | 104.35 | 0.00 | 0.20 | 0.20 | −47.63 | 0.22 |
| pCO2 offset | 4 | 104.35 | 0.00 | 0.20 | 0.41 | −47.63 | 0.20 |
| Life stage | 5 | 105.41 | 1.06 | 0.12 | 0.53 | −46.87 | 0.23 |
| Class | 7 | 105.47 | 1.12 | 0.12 | 0.64 | −44.09 | 0.30 |

Only top models [i.e., lowest AIC and highest log likelihood (LL in table)] are shown.
Figure 3. Responses of shellfish behavioral prey defenses to ocean acidification across taxonomic class. Mean effect sizes (lnRR ± bootstrapped BCa 95% CIs) for five classes of shellfish: malacostracans (white), echinoids (light gray), gastropods (gray), cephalopods (dark gray), and bivalves (black), with all pCO2 anomalies included (A) and only near-future pCO2 anomalies included (B). Values in parentheses indicate the number of observations used to derive the mean effect size for each taxon. Asterisks denote significant responses (i.e., when 95% CI does not overlap with 0). Negative and positive values correspond to negative and positive functional effects, respectively.

Meta-Analysis Results in a Broader Context

Taxonomic class consistently appeared in the best AIC models as a predictor of effect sizes. Although previous meta-analyses on biological responses to ocean acidification include taxonomy as an explanatory variable, those studies typically select phylum as the taxonomic resolution at which to test differences (Kroeker et al. 2010, 2013, Harvey et al. 2013). The results of the meta-analysis suggest that, at least for calcifying organisms, this level of taxonomy may be too broad and that using finer scales of taxonomic resolution may provide better predications of ocean acidification sensitivity. It is important to note, however, that class alone was unable to explain much of the variation in observed effect sizes herein ($R^2 = 0.27$ for near-future $p$CO2), and as such may not be a fine enough taxonomic scale to explain observed differences. Such results highlight the importance of species-specific biology. Furthermore, Q-tests of heterogeneity revealed significant variation across studies within each taxonomic class (Table 3), suggesting that other processes are certainly involved in explaining ocean acidification effects on behavioral defenses of shellfish reported in the experimental studies reviewed here. Such variation could be explained by some variable(s) not included in the analysis (such as the type of behavior, the biological state of the test animals, local adaptation, or mismatches between experimental exposures and natural conditions), and may largely reflect unaccounted experimental artifacts that differed across studies.

When all $p$CO2 conditions were considered, a significant negative effect size was observed for the behavioral defenses of malacostracan and bivalve prey, whereas effect sizes for gastropods and echinoderms were not significantly different from zero; in addition, cephalopods exhibited a significant positive effect size. These results are in contrast with previous meta-analyses reporting mostly null effects of elevated $p$CO2 on crustacean taxa and sensitivities in molluscs and echinoderms (Kroeker et al. 2010, 2013, Harvey et al. 2013, Whittman & Pörtner 2013). Previous meta-analyses have excluded metrics of behavior for shellfish taxa likely because too few studies were available (see Fig. 2A). The results of this study suggest that impacts of ocean acidification on other biological processes of

| TABLE 3. Results of effect size analysis, including mean effect size, bootstrapped 95% CIs, Q-test results, and Rosenberg fail-safe test results. |
|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                   | Effect size     | Q-test          | Rosenberg FSN   |                  |                  |                  |                  |
|                   | Mean       | Upper CI  | Lower CI   | Df | Q     | P value | Rosenberg FSN |
| All $p$CO2       |            |            |            |    |       |         |                |
| Bivalvia         | -0.6075   | -0.1862   | -1.8144   | *  | 8    | 263.8  | <0.001        | 445             |
| Cephalopoda      | 0.9980    | 1.8897    | 0.3292    | *  | 3    | 14.6   | 0.002         | 7               |
| Gastropoda       | -0.0563   | 0.3380    | -0.3159   | —  | 28   | 599.6  | <0.001        | 1,281           |
| Echnoidea        | 0.0063    | 0.1046    | -0.1494   | —  | 8    | 15.9   | 0.044         | 0               |
| Malacostracca    | -0.3333   | -0.2243   | -0.5840   | *  | 11   | 45.4   | <0.001        | 507             |
| Adult            | -0.0572   | 0.2446    | -0.3163   | —  | 40   | 847.0  | <0.001        | 2,723           |
| Juvenile         | -0.6265   | -0.4272   | -0.8667   | *  | 8    | 22.3   | 0.004         | 265             |
| Larvae           | -0.0797   | 0.0120    | -0.2490   | —  | 12   | 192.6  | <0.001        | 140             |
| Near-future $p$CO2 |            |            |            |    |       |         |                |
| Bivalvia         | -0.2860   | -0.0021   | -0.9119   | *  | 2    | 33.8   | <0.001        | 0               |
| Cephalopoda      | 0.9980    | 1.8897    | 0.3076    | *  | 3    | 14.6   | 0.002         | 7               |
| Gastropoda       | -0.1263   | 0.2876    | -0.3279   | —  | 25   | 399.3  | <0.001        | 1,021           |
| Echnoidea        | -0.0195   | 0.1230    | -0.1591   | —  | 5    | 14.7   | 0.012         | 0               |
| Malacostracca    | -0.2920   | 0.1218    | -0.6340   | —  | 2    | 6.3    | 0.043         | 11              |
| Adult            | 0.1143    | 0.5896    | -0.1901   | —  | 22   | 295.9  | <0.001        | 0               |
| Juvenile         | -0.5679   | -0.3839   | -0.8261   | *  | 7    | 17.2   | 0.016         | 194             |
| Larvae           | -0.1009   | 0.0095    | -0.2878   | —  | 10   | 179.9  | <0.001        | 151             |

Asterisks denote significant effect sizes.
shellfish such as physiology and survival may not be adequate in defining effects on shellfish behaviors. It is important to note, however, that the negative effect sizes for malacostracans observed in this study were driven by higher-than-projected pCO2 conditions, as significant negative effects on malacostracans became nonsignificant when only near-future pCO2 changes were considered. More confident predictions of shellfish behavioral defenses under near-future pCO2 changes across classes, however, await further investigation, as sample sizes herein were relatively low (i.e., meta-analysis with only near-future pCO2 conditions were robust; see Rosenthal fail-safe numbers in Table 3).

Life stage was also a fixed factor that consistently appeared in the best models based on AIC model selection. Effect size analysis revealed that juvenile mean effect sizes were significantly lower than zero when all and only near-future pCO2 conditions were considered; larval and adult effect sizes were not significantly different from zero. Previous meta-analyses also highlight the importance of life stage (e.g., Kroeker et al. 2010, 2013, Harvey et al. 2013); however, those previous studies typically report that earlier life stages (i.e., larvae and juveniles) are more susceptible to ocean acidification than later life stages. By contrast, the meta-analysis detected no significant effect on the self-righting response (i.e., recovery in orientation after displacement); however, ocean acidification and warming acted synergistically, causing a net negative effect on decision time, whereas warming antagonistically reversed the effect of ocean acidification on route-finding ability.

**A QUALITATIVE ASSESSMENT OF OCEAN ACIDIFICATION EFFECTS IN THE CONTEXT OF WARMING**

Studies assessing the combined effects of ocean acidification and warming on shellfish prey defense behaviors were less common than acidification-only studies (n = 7 acidification–warming studies; 21% of all studies), with one reporting on a bivalve, five reporting on gastropods, and one on a malacostracan crustacean (Table 4). A meta-analysis of acidification–warming effects on behavioral prey defenses was not conducted, given the low number of available studies, and thus acidification–warming studies are described qualitatively. All acidification–warming studies used temperature increases consistent with near-future predictions (2°C–5°C), with the exception of Zhang et al. (2014), who used a temperature increase of 14°C (Table 4).

In the single study on bivalves, increased seawater temperature reversed the effect of sediment acidification on the burrowing behavior of juvenile *Mya arenaria* (Clements et al. 2017), whereas the single study on a malacostracan crustacean reported no effect of ocean acidification or warming on the self-righting response of adult *Hyas araneus* (Zittier et al. 2013). In gastropods, effects of ocean acidification and warming varied within and across species. For juvenile *Concholepas concholepas*, there was no effect of ocean acidification or warming on behavioral lateralization (i.e., right–left turning preference), movement time, or self-righting response (i.e., recovery in orientation after displacement); however, ocean acidification and warming acted synergistically, causing a net negative effect on decision time, whereas warming antagonistically reversed the effect of ocean acidification on route-finding ability.
| Reference          | Species                        | Climate region | Life stage | Behavioral metric       | Acclim. time | \( p\text{CO}_2 \) offset | Temperature offset | Effect of warming on ocean acidification response                                                                 |
|--------------------|-------------------------------|----------------|------------|-------------------------|--------------|-----------------------------|-------------------|------------------------------------------------------------------------------------------------------------------|
| Bivalves \((n = 1)\) | *Mya arenaria*               | Temperate      | Juvenile   | % burrowed              | 0            | 7,041                       | 2                 | Antagonistic effect of warming on ocean acidification response                                                   |
| Clements et al. (2017) |                               |                |            |                         |              |                             |                   |                                                                                                                  |
| Gastropods \((n = 5)\) | *Concholepas concholepas*     | Tropical       | Juvenile   | Absolute lateralization | 180          | 860                         | 3                 | No effect of warming on ocean acidification response                                                                      |
| Domenici et al. (2017) |                               |                |            | Movement duration       |              |                             |                   |                                                                                                                  |
|                      |                               |                |            | Decision time           |              |                             |                   | No effect of warming on ocean acidification response                                                                      |
|                      |                               |                |            | Route finding           |              |                             |                   | Synergistic effect of warming on ocean acidification response (OA effect only under warming)                         |
|                      |                               |                |            |                         |              |                             |                   | Antagonistic effect of warming on ocean acidification response                                                  |
| Manríquez et al. (2016) | *Concholepas concholepas*    | Tropical       | Juvenile   | Self-righting time      | 90           | 860                         | 4                 | No effect of warming on ocean acidification response                                                                      |
| Quiéros et al. (2014)  | *Nucella lapillus*            | Temperate      | Adult      | Speed                   | 425          | 164                         | 3                 | Antagonistic effect of warming on ocean acidification response                                                  |
| Schram et al. (2014)   | *Nacella concinna*            | Polar          | Adult      | Escape speed            | 42           | 545                         | 2                 | No effect of warming on ocean acidification response                                                                      |
|                       | *Margaretella antarctica*    | Polar          | Adult      | Self-righting time      | 42           | 545                         | 2                 | Warming reversed ocean acidification effect                                                            |
|                       |                               |                |            | Escape speed            |              |                             |                   | Warming reversed ocean acidification effect                                                            |
| Zhang et al. (2014)    | *Nassarius festivus*          | Tropical       | Larvae     | Swimming speed          | 1            | 499                         | 14                | Warming increased swimming speed; no ocean acidification effect                                                   |
|                       |                               |                |            |                         |              |                             |                   | Warming increased swimming speed; no ocean acidification effect                                                   |
|                       |                               |                |            |                         |              |                             |                   | Antagonistic effect of warming on ocean acidification response                                                   |
|                       | *Nassarius conoidalis*        | Tropical       | Larvae     | Swimming speed          | 1            | 499                         | 14                | Warming increased swimming speed; no ocean acidification effect                                                   |
|                       |                               |                |            |                         |              |                             |                   | Warming increased swimming speed; no ocean acidification effect                                                   |
| Malacostracans \((n = 1)\) | *Hyas araneus*               | Polar          | Adult      | Self-righting time      | 12           | 461                         | 3                 | No effect of warming or acidification                                                                                 |
| Zittler et al. (2013)  |                               |                |            |                         |              |                             |                   | No effect of warming or acidification                                                                             |
|                      |                               |                |            |                         |              |                             |                   | No effect of warming or acidification                                                                             |

Studies are ordered chronologically within each respective taxonomic class. Acclimation time is reported in days; \( p\text{CO}_2 \) is reported in \( \mu \text{atm} \); temperature is reported in °C.
(Manriquez et al. 2016, Domenici et al. 2017). Under 500 and 900 µatm increases in pCO_2, warming increased swimming speed in Nassarius festivus, whereas ocean acidification had no effect (Zhang et al. 2014). By contrast, ocean acidification significantly reduced the swimming speed of Nassarius conoidalis, and although warming did not impact the ocean acidification effect under the 500 µatm increase in pCO_2, warming partially alleviated the effect of ocean acidification under an 894 µatm pCO_2 increase (Zhang et al. 2014). Warming was also reported to reverse the ocean acidification effect on speed in adult Nucella lapillus (Quiéros et al. 2014). For two Antarctic gastropods, warming did not influence the negative effect of ocean acidification on the escape speed of Nucella concinna but reversed the effect of ocean acidification on the escape speed and self-righting response in Margarella antarctica (Schram et al. 2014).

Although the low number of studies precludes any confident conclusions regarding the combined effects of ocean acidification and warming on shellfish behavioral defenses, it is clear that multiple stressor effects most often differ from single stressor impacts. Of the total number of species (n = 8) in the seven studies highlighted earlier, 75% (n = 6) exhibited different responses when both ocean acidification and warming were considered in combination when compared with ocean acidification considered alone; the combined effects were variable (Table 4). It is thus clear that the effect of ocean acidification on shellfish behavioral defenses can be influenced by seawater temperature and that future ocean warming is likely to influence the impact of ocean acidification on this behavioral response.

**NEUROLOGICAL IMPAIRMENT AS A DRIVING MECHANISM**

Recent studies have suggested a potential biological mechanism underpinning behavioral sensitivity to elevated pCO_2: GABA_A neurotransmitter interference (see Tresguerres & Hamilton 2017 for review). In short, this hypothesis suggests that directional shifts in ionic gradients at GABA_A neuroreceptors can occur under elevated pCO_2, which can ultimately drive increased neuronal depolarization and neural pathway excitation, resulting in altered animal behavior (Nilsson et al. 2012, Hamilton et al. 2014, Tresguerres & Hamilton 2017). To explore this hypothesis in relation to ocean acidification, studies often dose experimental animals with the GABA_A inhibitor gabazine. Gabazine effectively closes the GABA_A neuroreceptor, preventing neuronal depolarization and altered behavior; thus, if GABA_A interference is driving a behavioral alteration under elevated pCO_2, one would predict that the behavior of animals treated with gabazine would be unaltered by elevated pCO_2, whereas that of animals not treated with gabazine would be altered. Although numerous studies have demonstrated this mechanism in fishes (Nilsson et al. 2012, Chivers et al. 2014, Chung et al. 2014, Hamilton et al. 2014, Lai et al. 2015, Ou et al. 2015, Lopes et al. 2016, Regan et al. 2016), only a handful of studies have tested this hypothesis for shellfish taxa. In this section, these studies were assessed qualitatively (because of a low number of studies as with the aforementioned acidification–warming literature) to highlight the potential role of GABA_A interference in driven behavioral effects of ocean acidification in invertebrates.

The literature search uncovered three studies that empirically tested the “GABA_A hypothesis” on prey defenses in shellfish. Watson et al. (2014) first tested this hypothesis in the adult snail *Gibberula gibberula gibbosus* from Australia that “jump” away from predators to escape predation. Therein, it was reported that exposure to ocean acidification conditions negatively affected jumping ability in the snails, but that treatment with gabazine restored the jumping behavior under ocean acidification. Since then, this same result has been shown for burrowing responses in temperate bivalves (juvenile *Mya arenaria*: Clements et al. 2017) and malacostracans (adult *Corophium volutator*: Walsh 2018) to CO_2-driven sediment acidification. Walsh (2018) also tested this hypothesis on burrowing behavior for the adult snail *Tritia obsoleta*; however, the burrowing behavior of this species was unaffected by sediment acidification. Furthermore, although the direct effect of GABA_A neuroreceptor interference was not directly tested on a specific behavior(s), Moya et al. (2016) reported that genes related to GABA_A neuroreceptor structure and function in the pteropods *Heliconoides inflatus* were upregulated under elevated pCO_2 (along with other genes associated with the nervous system).

These results suggest that GABA_A interference under elevated pCO_2 may be an important driver in the behavioral responses of marine shellfish. Further investigation into the universality of this biological mechanism for altered behavior in shellfish and other invertebrates under ocean acidification is thus warranted. It is important to note, however, that altered GABA_A functioning is not the only biological mechanism that can drive ocean acidification effects on prey defense behaviors (and other behaviors) in shellfish. For example, morphological and other physiological effects of elevated pCO_2 have the potential to affect performance and activity behaviors related to prey defense such as locomotion (Watson et al. 2017) and self-righting ability (Manriquez et al. 2013). Ultimately, although GABA_A interference appears to play a substantial role in ocean acidification effects on shellfish behavioral defenses, further research on this and other mechanisms is needed.

**KNOWLEDGE GAPS AND CONSIDERATIONS FOR FUTURE RESEARCH**

**Multiple Stressors**

Although some information pertaining to the interactive effects of ocean acidification and warming on shellfish behavioral defenses was gleaned, the combined effects of ocean acidification and other global change stressors are understudied. Of the 34 studies identified here, only one assessed the effects of ocean acidification in the context of a stressor other than temperature: Zhang et al. (2014) assessed the combined effects of pCO_2, temperature, and salinity on the swimming performance of two gastropods, *Nassarius festivus* and *Nassarius conoidalis*. Therein, it was reported that elevated pCO_2 reduced swimming speed in *N. conoidalis* (but not in *N. festivus*) and that higher temperature and higher salinity increased the swimming speed for both species.

Despite the lack of multistressor studies on shellfish behavioral defenses, it is widely known that responses to ocean acidification can depend on other stressors such as temperature, hypoxia and deoxygenation, salinity, and eutrophication, which can act synergistically or antagonistically with ocean acidification to drive biological responses (Pörtner 2008, Wallace et al. 2014, Breitburg et al. 2015). Food web structure and food supply are also considered to have impacts on biological responses to ocean acidification (Alsterberg et al. 2013, Ramajo et al. 2015,
Goldenberg et al. 2018, Swat et al. 2018). Adding to such complexities, ocean acidification can affect organismal affinity and selection for particular environmental conditions (e.g., temperature and salinity preferences as per Pistevos et al. 2017). Although not assessed in shellfish, studies have assessed ocean acidification effects in the context of some additional stressors on antipredator behaviors in fishes. For example, McMahon et al. (2018) reported that food availability had no influence on ocean acidification–induced effects on antipredator behavior in the juvenile clownfish Amphiprion percula. By contrast, Miller et al. (2016) found that ocean acidification exposure led to increased surface ventilating behavior under low oxygen in congeneric fishes Menidia menidia and Menidia beryllina, which could potentially lead to increased vulnerability to aerial predators. Such complex effects highlight the importance of considering multiple global change stressors in predicting how the behavioral prey defenses of marine fauna will be impacted in a future ocean. When it comes to shellfish, more research is necessary, as research has yet to even scrape that surface.

Environmental Variability

As mentioned previously, coastal systems are often characterized by a high degree of spatial and temporal carbonate system variability (Provoost et al. 2010, Duarte et al. 2013, Waldbusser & Salisbury 2014, Wallace et al. 2014), which is likely to increase in the future (Kwiatkowski & Orr 2018, Pacella et al. 2018). From an organismal perspective, such variability is far from benign and can influence biological responses to ocean acidification in a number of potential ways (Helmuth et al. 2014, Waldbusser & Salisbury 2014, Bates et al. 2018). For example, a high degree of abiotic variability may confer tolerance to a wide range of environmental conditions in some coastal organisms, rendering them robust to relatively small baseline changes over long periods of time (i.e., many generations). Consequently, in coastal marine systems, pCO₂ variability is an important consideration in understanding biological responses to ocean acidification (Waldbusser & Salisbury 2014).

In the context of shellfish behavioral defenses, two of the 34 studies identified in this review assessed ocean acidification effects in the context of pCO₂ variability, reporting conflicting results. In a pioneering study, Alenius and Munguia (2012) showed that variable high pCO₂ conditions resulted in negative effects to locomotory behavior in the adult isopod Parapedilia dianae, whereas stable high pCO₂ conditions had no effect. By contrast, Jellison et al. (2016) reported no difference between stable and fluctuating CO₂ conditions on predator avoidance behaviors in the adult snail Tegula funebralis. Although the paucity of information regarding the role of pCO₂ variability (along with variability in other environmental parameters) in shaping the responses of shellfish behavioral defenses precludes firm conclusions, the contrasting results observed here underscore the importance and complexity of such variability.

Evolutionary Effects

An increasingly popular topic in contemporary ocean acidification research concerns the role of evolution and plasticity in biological responses to ocean acidification (Sunday et al. 2014, Calosi et al. 2016). Evolutionary forces such as local adaptation (Vargas et al. 2017) and natural selection (Thomsen et al. 2017), along with acclimatory processes such as transgenerational plasticity (Parker et al. 2012, 2015, Borges et al. 2018), can play important roles in shellfish responses to ocean acidification, both in isolation and in the presence of other co-occurring stressors (Gibben et al. 2017, Griffith & Gobler 2017). The literature search revealed no articles testing for evolutionary or acclimatory effects on shellfish behavioral defense responses to ocean acidification. Furthermore, a broader search of the literature suggested that evolutionary studies for invertebrate behaviors (in a broad sense) under ocean acidification remain absent (Ross et al. 2016), with the exception of a recent study reporting that transgenerational acclimation did not alleviate ocean acidification effects on mate guarding in the amphipod Gammarus locusta (males guard females from competing mates) (Borges et al. 2018).

Although evolutionary studies of shellfish behavioral defenses are not yet available, studies to this regard in fish may shed some light on potential effects in shellfish. For example, Welch et al. (2014) observed no evidence that transgenerational acclimation affected offspring behavioral responses (behavioral lateralization) to ocean acidification conditions in Acanthochromis polyacanthus. In a follow-up study on the same species, Welch and Munday (2017) demonstrated that although acute exposure to elevated pCO₂ elicited heritable behavioral phenotypes in response to predators, prolonged (four week) exposure to elevated pCO₂ negated the observed heritability under acute exposure. Ultimately, the influences of evolution and transgenerational plasticity on behavioral responses of shellfish to ocean acidification deserve attention, particularly given the variable impacts that these processes can have on shellfish responses to ocean acidification (Ross et al. 2016).

Ecological Complexity

The experiments reviewed herein suggest that ocean acidification can potentially influence behavioral defenses in shellfish prey, based primarily on laboratory observations of individual behaviors under control and elevated pCO₂ conditions. Predicting how and whether such changes might manifest themselves under natural conditions is difficult, however, because of the inherent situational and ecological complexity of nature (i.e., the breadth of other things that are occurring in natural systems). For example, individual personalities within a group of organisms can affect group-level responses to predation (Briffa et al. 2008). Similarly, immediate and prior exposures to the risk of predation (e.g., through predator-produced kairomones or through conspecific alarm cues) can influence behavioral prey defenses in shellfish (Hagen et al. 2002, Briffa 2013). Strikingly, of the studies reviewed herein, only 15% (n = 5 of 34) included predator cues in their experiments testing for effects of ocean acidification on prey defense behaviors (Bibby et al. 2007, Hatfield-Vaughan 2011, Manriquez et al. 2014, Watson et al. 2014, Jellison et al. 2016). This important situational caveat calls into question the transferability of many of these experiments to natural conditions. Studies including predator cues, however, have still reported significant ocean acidification effects on shellfish defense behaviors, suggesting that behavioral alterations can still affect predator–prey ecology in systems involving shellfish prey (Manriquez et al. 2014, Watson et al. 2014, Jellison et al. 2016).
Other nuances of natural biological communities can likely influence shellfish behavioral defense responses to ocean acidification as well. Recent studies have suggested that although ocean acidification may directly affect individual behaviors of organisms, increased diversity within biological systems may allow for compensatory processes to offset negative direct behavioral effects related to consumer foraging (Goldenberg et al. 2018; although they did note that increases in risky behavior under ocean acidification may make prey more vulnerable to predation). Ultimately, the situational conditions within complex ecological systems may impact shellfish behavioral defenses against predation in a high CO₂ ocean and thus warrant exploration. Furthermore, an understanding of how such behavioral changes influence ecological structure and function is required to understand and predict the ecological consequences of ocean acidification.

Functional Trade-offs

Engaging (or not engaging) in a particular defense behavior may not only affect the vulnerability of an organism to predation but can also result in functional trade-offs with other biological processes. For example, Bridger et al. (2015) reported that bolder male hermit crabs Pagurus bernhardus experience lower fecundity than less bold males. Consequently, if ocean acidification results in increased boldness and risk-taking behavior in a given species, not only would vulnerability to predation increase but fecundity may also decrease. Such additive negative effects could have major implications for the ecological functioning of biological communities. These interactions between biological processes may not always be additive or negative, however. For example, although reduced burrowing capacity under sediment acidification (Clements & Hunt 2017) conditions can make bivalves more vulnerable to predation (Flynn & Smee 2010), this behavioral response also allows bivalves to avoid other mortality sources such as shell dissolution (Green et al. 2004, 2009). Ultimately, the complex trade-offs between defense behaviors and other biological processes that drive net fitness outcomes and the capacity of organisms to survive and persist under ocean acidification deserve attention.

CONCLUSIONS

This review ultimately suggests that controlled laboratory exposure to elevated pCO₂ can affect prey defense behaviors in marine shellfish. Meta-analysis results suggested that bivalves and malacostracan crustaceans are likely vulnerable to ocean acidification effects on defense behaviors; however, effects on malacostracans may be contingent on the degree of pCO₂ elevation, as negative effect sizes were primarily driven by normally high pCO₂ conditions. A major shortcoming of most studies reviewed here, however, is that prey defense behaviors were not tested in the presence of predator cues (kairomones or prey alarm cues)—a component of predator–prey interactions that is necessary for realistic ecological predictions. Although more research is needed, a qualitative review of a handful of studies on the combined effects of ocean acidification and warming suggested that coincident increases in seawater temperature are important to consider when testing for ocean acidification effects in the context of long-term global change and coastal variability; the combined effects of ocean acidification and other stressors, and the effect of temporal and spatial environmental variability, require further research. Although many questions pertaining to ocean acidification effects on shellfish behavior and defenses remain to be tested, studies on fish may help streamline hypotheses and experimental approaches, particularly given the common theme of GABA inhibition across these widely different taxa. Given the importance of prey defense behaviors to the structure and function of marine biological communities, increased research efforts into this topic are warranted and would contribute to a more holistic understanding of the ecological effects of ocean acidification.

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DATA ACCESSIBILITY

Annotated R-script, all raw data files, and a complete dataset are available online from Mendeley Data at https://dx.doi.org/10.17632/vwtfrrjym.2.

LITERATURE CITED

Adams, D. C., J. Gurevitch & M. S. Rosenberg. 1997. Resampling tests for meta-analysis of ecological data. Ecology 78:1277–1283.
Alcaraz, G. & E. Arce. 2017. Predator discrimination in the hermit crab Calcinus californiensis: tight for shell breakers, loose for shell peelers. Oikos 126:1299–1307.
Alenius, B. & P. Munguia. 2012. Effects of pH variability on the intertidal isopod, Paradella dianae. Mar. Freshw. Behav. Physiol. 45:245–259.
Alsterberg, C., J. S. Eklöf, L. Gamfeldt, J. N. Havenhand & K. Alenius. 2012. Effects of pH variability on the intertidal hermit crab Pagurus bernhardus. Marine biology. 159:2481–2491.
Alsterberg, C., J. S. Eklöf, L. Gamfeldt, J. N. Havenhand & K. Alenius. 2012. Effects of pH variability on the intertidal hermit crab Pagurus bernhardus. Marine biology. 159:2481–2491.
Alsterberg, C., J. S. Eklöf, L. Gamfeldt, J. N. Havenhand & K. Sundbäck. 2013. Consumers mediate the effects of experimental ocean acidification and warming on primary producers. Proc. Natl. Acad. Sci. USA 110:8603–8608.
Alsterberg, C., J. S. Eklöf, L. Gamfeldt, J. N. Havenhand & K. Sundbäck. 2013. Consumers mediate the effects of experimental ocean acidification and warming on primary producers. Proc. Natl. Acad. Sci. USA 110:8603–8608.
Barkai, A. & C. McQuaid. 1988. Predator-prey role reversal in a marine benthic ecosystem. Science 242:62–64.
Barry, J. P., C. Lovera, K. R. Buck, E. T. Peltzer, J. R. Taylor, P. Walz, P. J. Whaling & P. G. Brewer. 2014. Use of a free ocean CO₂ enrichment (FOCE) system to evaluate the effects of ocean acidification on the foraging behavior of a deep-sea urchin. Environ. Sci. Technol. 48:9890–9897.
Barton, K. 2018. MuMIn: multi-model inference. Available at: https://cran.r-project.org/web/packages/MuMIn/index.html.
Bates, A. E., B. Helmuth, M. T. Burrows, M. I. Duncan, J. Garrabou, T. Guy-Haim, F. Lima, A. M. Quiros, R. Seabra, R. Marsh,
OCEAN ACIDIFICATION AND BEHAVIORAL DEFENSES

J. Belmaker, N. Bensoussan, Y. Dong, A. D. Mazaris, D. Smale, M. Wahl & G. Rilov. 2018. Biologists ignore ocean weather at their peril. *Nature* 560:299–301.

Belgrad, B. A. & B. D. Griffen. 2016. Predator-prey interactions mediated by prey personality and predator hunting mode. *Proc. Biol. Sci.* 283:e20160408.

Bibby, R., P. Cleall-Harding, S. Rundle, S. Widdicombe & J. Spicer. 2007. Ocean acidification disrupts induced defences in the intertidal gastropod *Littorina littorea*. *Lett. Biol.* 3:699–701.

Borges, F. O., C. Figueiredo, E. Sampaio, R. Rosa & T. F. Grilo. 2018. Transgenerational deleterious effects of ocean acidification on the reproductive success of a keystone crustacean (*Gammarus locusta*). *Mar. Environ. Res.* 138:55–64.

Breitbart, D. L., J. Salisbury, J. M. Bernhard, W.-J. Cai, S. Dupont, S. C. Donley, K. J. Kroeker, L. A. Levin, W. C. Long, L. M. Milke, S. H. Miller, B. Phelan, U. Passow, B. A. Seibel, A. E. Tothgum & A. M. Tarrant. 2015. And on top of all that... coping with ocean acidification in the midst of many stressors. *Oceanography* 28:48–61.

Brigger, D., S. J. Bonner & M. Briffa. 2015. Individual quality and personality: bolder males are less fecund in the hermit crab *Pagurus bernhardus*. *Proc. Biol. Sci.* 282:20142492.

Briffa, M. 2013. Plastic proteins: reduced predictability in the face of predation risk in hermit crabs. *Biol. Lett.* 9:20130592.

Briffa, M., D. Bridger & P. A. Biro. 2013. How does temperature affect behaviour? Multilevel analysis of plasticity, personality and predictability in hermit crabs. *Anim. Behav.* 86:47–54.

Briffa, M., K. de la Haye & P. L. Munday. 2012. High CO2 and marine animal behaviour: potential mechanisms and ecological consequences. *Mar. Pollut. Bull.* 64:1519–1528.

Briffa, M., S. D. Rundle & A. Fryer. 2008. Comparing the strength of behavioural plasticity and consistency across situations: animal personalities in the hermit crab *Pagurus bernhardus*. *Proc. Biol. Sci.* 275:1305–1311.

Burnham, K. P. & D. R. Anderson. 2002. Model selection and multimodal inference: a practical information-theoretic approach. New York, NY: Springer.

Calosi, P., P. DeWit, P. Thor & S. Dupont. 2016. Will life find a way? Evolution of marine species under global change. *Ecol. Appl.* 9:1035–1042.

Canty, A. & B. Ripley. 2017. boot: Bootstrap R (S-Plus) functions. Available at: https://cran.r-project.org/web/packages/boot/index.html.

Chan, K. Y. K., D. Grünbaum, M. Arnborg & S. Dupont. 2016. Impacts of ocean acidification on survival, growth, and swimming behaviours differ between larval urchins and brittlestars. *ICES J. Mar. Sci.* 73:951–961.

Chan, K. Y. K., D. Grünbaum & M. J. O’Donnell. 2011. Effects of ocean-acidification-induced morphological changes on larval swimming and feeding. *J. Exp. Biol.* 214:3857–3867.

Chan, K. Y. K., E. Garcia & S. Dupont. 2015. Acidification reduced growth rate but not swimming speed of larval sea urchins. *Sci. Rep.* 5:1035–1042.

Chivers, D. P., M. I. McCormick, G. E. Nilsson, P. L. Munday, S.-A. Watson, M. G. Meekan, M. D. Mitchell, K. C. Corkill & M. C. O. Ferrari. 2014. Impaired learning of predators and lower prey survival under elevated CO2: a consequence of neurotransmitter interference. *Glob. Chang. Biol.* 20:515–522.

Chung, W. S., N. J. Marshall, S.-A. Watson, P. L. Munday & G. E. Nilsson. 2014. Ocean acidification slows retinal function in a damselfish through interference with GABAA receptors. *J. Exp. Biol.* 217:323–326.

Clements, J. C. & H. L. Hunt. 2014. Influence of sediment acidification and water flow on sediment acceptance and dispersal of juvenile soft-shell clams (*Mya arenaria* L.). *J. Exp. Mar. Biol. Ecol.* 453:62–69.

Clements, J. C. & H. L. Hunt. 2015. Marine animal behaviour in a high CO2 world. *Mar. Ecol. Prog. Ser.* 536:259–279.

Clements, J. C. & H. L. Hunt. 2017. Effects of CO2-driven sediment acidification on infaunal marine bivalves: a synthesis. *Mar. Pollut. Bull.* 117:6–16.

Clements, J. C., K. D. Woodard & H. L. Hunt. 2016. Porewater acidification alters the burrowing behavior and post-settlement dispersal of juvenile soft-shell clams (*Mya arenaria*). *J. Exp. Mar. Biol. Ecol.* 477:103–111.

Clements, J. C., M. M. Bishop & H. L. Hunt. 2017. Elevated temperature has adverse effects on GABA-mediated avoidance behaviour to sediment aciddification in a wide-ranging marine bivalve. *Mar. Biol.* 164:56.

Connell, J. H. 1961. Effect of competition, predation by *Thais lapillus* and other factors on natural populations of the barnacle *Balanae balanoides*. *Ecol. Monogr.* 31:61–104.

Cotton, P. A., S. D. Rundle & K. E. Smith. 2004. Trait compensation in marine gastropods: shell shape, avoidance behavior, and susceptibility to predation. *Ecology* 85:1581–1584.

de la Haye, K. L., J. I. Spicer, S. Widdicombe & M. Briffa. 2011. Reduced sea water pH disrupts resource assessment and decision making in the hermit crab *Pagurus bernhardus*. *Anim. Behav.* 82:495–501.

de la Haye, K. L., J. I. Spicer, S. Widdicombe & M. Briffa. 2012. Reduced pH sea water disrupts chemo-responsive behaviour in an intertidal crustacean. *J. Exp. Mar. Biol. Ecol.* 412:134–140.

Dickson, A. G. & F. J. Millero. 1987. A comparison of equilibrium constants for the dissociation of carbonic acid in seawater media. *Deep Sea Res.* 34:1733–1743.

Domenici, P., R. Torres & P. H. Manriquez. 2017. Effects of elevated carbon dioxide and temperature on locomotion and the repeatability of lateralization in a keystone marine mollusc. *J. Exp. Biol.* 220:667–676.

Donney, S. C., V. J. Fabry, R. A. Feely & J. A. Kleypas. 2009. Ocean acidification: the other CO2 problem. *Annu. Rev. Mar. Sci.* 1:169–192.

Duarte, C. M., I. E. Hendriks, T. S. Moore, Y. S. Olsen, A. Steckbauer, L. Ramajo, J. Cartensen, J. A. Trotter & M. McCulloch. 2013. Is ocean acidification an open-ocean syndrome? Understanding anthropogenic impacts on seawater pH. *Estuar. Coasts* 36:221–236.

Fields, J. 2013. Effects of ocean acidification on the behavior of two marine invertebrates: a study of predator-prey responses of the mollusces *Conus marmoreus* and *Striombus liuhuanus* at elevated-CO2 conditions. SIT study abroad thesis, SIT Graduate Institute, Brattleboro, Vermont.

Flynn, A. M. & D. L. Smeet. 2010. Behavioral plasticity of the soft-shell clam, *Mya arenaria* (L.), in the presence of predators increases survival in the field. *J. Exp. Mar. Biol. Ecol.* 383:32–38.

Gibben, E. M., L. J. Chakravarti, M. D. Jarrold, F. Christen, V. Turpin, G. Massamba N’Siala, P. U. Blier & P. Calosi. 2017. Can multi-generational exposure to ocean warming and acidification lead to the adaptation of life history and physiology in a marine metazoan? *J. Exp. Biol.* 220:551–563.

Goldenberg, S. U., I. Nagelkerken, E. Marangon, A. Bonnet, C. M. Ferreira & S. D. Connell. 2018. Ecological complexity buffers the impacts of future climate on marine consumers. *Nat. Clim. Chang.* 8:229–233.

Green, M. A., G. G. Waldbusser, L. Hubacza, E. Cathecar & J. Hall. 2013. Carbonate mineral saturation state as the recruitment cue for settling bivalves in marine muds. *Estuar. Coasts* 36:18–27.

Green, M. A., G. G. Waldbusser, S. L. Reilly, K. Emerson & S. O’Donnell. 2009. Death by dissolution: sediment saturation state as a mortality factor for juvenile bivalves. *Linnol. Oceanogr.* 54:1037–1047.

Green, M. A., M. E. Jones, C. L. Boudreau, R. L. Moore & B. A. Westman. 2004. Dissolution mortality of juvenile bivalves in coastal marine deposits. *Linnol. Oceanogr.* 49:727–734.

Grilli, A. W. & C. J. Gobler. 2017. Transgenerational exposure of North Atlantic bivalves to ocean acidification renders offspring...
more vulnerable to low pH and additional stressors. *Sci. Rep.* 7:11394.

Hagen, N. T., A. Andersen & O. B. Stabell. 2002. Alarm responses of the green sea urchin, *Strongylocentrotus droebachiensis*, induced by chemically labelled diphosphoglycerate and simulated acts of predation. *Mar. Biol.* 140:365–374.

Heck, K. L. & T. A. Thoman. 1981. Experiments on predator-prey interactions in echinoderms. MSc thesis, University of British Columbia, Vancouver, Canada.

Hek, K. L. & T. A. Thoman. 1981. Experiments on predator-prey interactions in vegetated aquatic habitats. *J. Exp. Mar. Biol. Ecol.* 53:125–134.

Hedges, L. V. & I. Olkin. 1985. Statistical methods for meta-analysis. New York, NY: Academic Press.

Hedges, L. V., J. Gurevitch & P. S. Curtis. 1999. The meta-analysis of response ratios in experimental ecology. *Ecology* 80:1150–1156.

Harrell, F. E., Jr. 2017. Hmisc: Harrell miscellaneous. Available at: https://cran.r-project.org/package=Hmisc.

Harvey, B. P., D. Gwynn-Jones & P. J. Moore. 2013. Meta-analysis reveals complex marine biological responses to the interactive effects of ocean acidification and warming. *Ecol. Evol.* 3:1016–1030.

Hatfield-Vaughan, M. L. 2011. Effects of ocean acidification on predator-prey interactions in echinoderms. MSc thesis, University of British Columbia, Vancouver, Canada.

Hemmi, J. M. & T. Merkle. 2009. High stimulus specificity characterizes antipredator habituation under natural conditions. *Proc. Biol. Sci.* 276:4381–4388.

Hoegh-Guldberg, O., R. Cai, E. S. Poloczanska, P. G. Brewer, S. Sundby, K. Hilmi, V. J. Fabry & S. Jung. 2014. The ocean. In: Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastandrea & I. I. White, editors. Climate change 2014: impacts, adaptation, and vulnerability, New York, NY: Cambridge University Press. pp. 1655–1731.

Jellison, B. M., A. T. Ninokawa, T. M. Hill, E. Sanford & B. Gaylord. 2016. Ocean acidification alters the response of intertidal snails to a key sea star predator. *Proc. Biol. Sci.* 283:20160890.

Kim, T. W. & J. P. Barry. 2016. Boldness in a deep sea hermit crab to simulated tactile predator attacks is unaffected by ocean acidification. *Ocean Sci.* 12:381–386.

Kroeker, K. J., E. Sanford, B. M. Jellison & B. Gaylord. 2014. Predicting the effects of ocean acidification on predator-prey interactions: a conceptual framework based on coxal molluscs. *Biol. Bull.* 226:211–222.

Kroeker, K. J., R. L. Kordas, R. N. Crim & G. G. Singh. 2010. Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. *Ecol. Lett.* 13:1419–1434.

Kroeker, K. J., R. L. Kordas, R. N. Crim, I. E. Hendriks, L. Ramajo, G. G. Singh, C. M. Duarte & J.-P. Gattuso. 2013. Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. *Glob. Chang. Biol.* 19:1884–1896.

Kwitkowski, L. & J. C. Orr. 2018. Diversifying seasonal extremes for ocean acidification during the twenty-first century. *Nat. Clim. Chang.* 8:141–145.

Lai, F., F. Juttef, G. E. Nilsson, 2015. Altered neurotransmitter function in CO2-exposed stickleback (Gasterosteus aculeatus): a temperate model species for ocean acidification research. *Conserv. Physiol.* 3:cov018.

Lajeunesse, M. J. & M. R. Forbes. 2003. Variable reporting and quantitative reviews: a comparison of three meta-analytical techniques. *Ecol. Lett.* 6:448–454.

Lopes, A. F., P. Morais, M. Pimentel, R. Rosa, P. L. Munday, E. J. Gonçalves & A. M. Faria. 2016. Behavioural lateralization and shoaling cohesion of fish larvae altered under ocean acidification. *Mar. Biol.* 163:243.

Manriquez, P. H., M. E. Jara, M. E. Seguel, R. Torres, E. Alarcon & M. R. Lee. 2016. Ocean acidification and increased temperature have both positive and negative effects on early ontogenetic traits of a rocky shore keystone predator species. *PLoS One* 11:e0151920.

Manriquez, P. H., M. E. Jara, M. L. Mardones, J. M. Navarro, R. Torres, M. A. Lardies, C. A. Vargas, C. Duarte, S. Widdicombe, J. Salisbury & N. A. Lagos. 2013. Ocean acidification disrupts prey responses to predator cues but not prey net shell growth in *Concholepas concholepas* (locos). *PLoS One* 8:e68643.

Manriquez, P. H., M. E. Jara, M. L. Mardones, R. Torres, J. M. Navarro, M. A. Lardies, C. A. Vargas, C. Duarte & N. A. Lagos. 2014. Ocean acidification affects predator avoidance behaviour but not prey detection in the early ontogeny of a keystone species. *Mar. Ecol. Prog. Ser.* 502:157–167.

Mazerolle, M. J. 2017. Model selection and multimodel inference based on (Q)AIC(c). Available at: https://cran.r-project.org/web/packages/AICcmodavg/index.html.

McElhaney, P. 2017. CO2 sensitivity experiments are not sufficient to show an effect of ocean acidification. *ICES J. Mar. Sci.* 74:926–928.

McMahon, S. J., J. M. Donelson & P. L. Munday. 2018. Food ration does not influence the effect of elevated CO2 on antipredator behaviour of a reef fish. *Mar. Ecol. Prog. Ser.* 586:155–165.

Mehrbach, C., J. E. Culberson, J. E. Hawley & R. M. Pytkowicz. 1973. Measurements of apparent dissociation constants of carbonic acid in seawater at atmospheric pressure. *Limnol. Oceanogr.* 18:997–907.

Miller, S. H., D. L. Britenburg, R. B. Burrell & A. G. Keppel. 2016. Acidification increases sensitivity to hypoxia in important forage fishes. *Mar. Ecol. Prog. Ser.* 549:1–8.

Mima, A., S. Wada & S. Goshima. 2003. Antipredator defence of the hermit crab *Pagurus filholi* induced by predatory crabs. *Oikos* 102:104–110.

Moya, A., E. I. Howes, T. Lacouve-Labarithm, S. Forêt, B. Hanna, M. Medina, P. L. Munday, J.-S. Ong, J.-L. Teysgés, G. Torda, S.-A. Watson, D. J. Miller, J. Bjima & J.-P. Gattuso. 2016. Near-future pH conditions severely impact calcification, metabolism and the nervous system in the invertebrate *Helicoceros inflatus*. *Glob. Chang. Biol.* 22:3888–3900.

Munroe, D. J., K. Kraeuter, B. Beal, K. Chew, M. Luckenbach & C. P. Peterson. 2015. Clam predator protection is effective and necessary for food production. *Mar. Pollut. Bull.* 100:47–52.

Nagelkerken, I. & P. L. Munday. 2016. Animal behaviour shapes the ecological effects of ocean acidification and warming: moving from individual to community-level responses. *Glob. Chang. Biol.* 22:974–989.

Nakagawa, S., R. Poulin, K. Mengersen, K. Reinhold, L. Engqvist, M. Lagisz & A. M. Senior. 2015. Meta-analysis of variation: ecological and evolutionary applications and beyond. *Methods Ecol. Evol.* 6:143–152.

Nilsson, G. E., D. L. Dixson, P. Domenici, M. I. McCormick, C. Sørensen, S.-A. Watson & P. L. Munday. 2012. Near-future carbon dioxide levels alter fish behaviour by interfering with neurotransmitter function. *Nat. Clim. Chang.* 2:201–204.

Noble, D. W., M. Lagisz, R. E. O’Dea & S. Nakagawa. 2017. Non-independence and sensitivity analyses in ecological and evolutionary meta-analyses. *Mol. Ecol.* 26:2410–2425.

Orr, J. C., V. J. Fabry, O. Aumont, L. Bopp, S. C. Doney, R. A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, R. M. Key, K. Lindsay, M. A. Leifer-Reimer, R. Matear, P. Monfray, A. Mouchet, R. G. Najjar, G.-K. Plattner, K. R. Rogers, C. L. Sabine, J. L. Sarmiento, R. Schütz, R. D. Slater, I. J. Todderell, M.-F. Weirig, Y. Yamanaka & A. Yool. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature* 437:681–686.
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Orth, R. J., K. L. Heck & J. van Manffrans. 1984. Faunal communities in seagrass beds: a review of the influence of plant structure and prey characteristics on predator-prey relationships. Estuaries 7:339–350.

Pacella, S. R., C. A. Brown, G. G. Waldbusser, R. G. Labiosa & B. Hales. 2018. Seagrass habitat metabolism increases short-term extremes and long-term offset of CO2 under future ocean acidification. Proc. Natl. Acad. Sci. USA 115:3870–3875.

Paine, R. T. 1966. Food web complexity and species diversity. Am. Nat. 100:65–75.

Paine, R. T. & D. E. Schindler. 2002. Ecological pork: novel resources

Pistevos, J. C., I. Nagelkerken, T. Rossi & S. D. Connell. 2017. Ocean acidification alters the burrowing behavior, Ca2+/Mg2+-ATPase activity, metabolism, and gene expression of a bivalve species, Sinonovacula constricta. Mar. Ecol. Prog. Ser. 575:107–117.

Petter, C. H. 1982. The importance of predation and intra- and interspecific competition in the population biology of two infaunal suspension-feeding bivalves, Protobranchia staminea and Chione undata. Ecol. Monogr. 52:437–475.

Pierrot, D., E. Lewis & D. W. R. Wallace. 2006. MS Excel program developed for CO2 system calculations. ORNL/CDIAC-105a. Tennessee: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy.

Pörtner, H.-O. 2008. Adult exposure influences offspring response to ocean acidification in oysters. Glob. Chang. Biol. 14:82–92.

Pörtner, H.-O., M. A. K. Aitken, D. A. Raftos & H.-O. Pörtner. 2012. Adult exposure influences offspring response to ocean acidification in oysters. Glob. Chang. Biol. 18:19–32.

Pörtner, H.-O. 2015. Persistence of positive carryover effects in the oyster, Crassostrea virginica, in response to variable CO2 levels. Proc. Natl. Acad. Sci. USA 112:4794–4799.

Querós, A. M., J. A. Fernandes, S. Faulwetter, J. Nunes, S. P. S. Rastrick, N. Mieszowska, Y. Artioli, A. Yool, P. Calosi, C. Arvanitidis, H. S. Findley, M. Barange, W. L. Cheung & S. Widdicombe. 2017. Marine systems to assess species-specific responses to ocean acidification: a review of the influence of plant structure and prey characteristics on predator-prey relationships. Estuaries 7:339–350.

Provoost, P., S. Heuven, K. Soetaert, R. W. P. M. Laane & K. M. Wegner & F. Melzner. 2017. Naturally acidified habitats selects for ocean acidification–tolerant mussels. Helgoländer wiss. Meeresunters. 71:109–118.

Richardson, J. M. L. 2001. A comparative study of activity levels in larval anurans and response to the presence of different predators. Behav. Ecol. 12:51–58.

Ries, J. B., A. L. Cohen & D. C. McCorkle. 2009. Marine calcifiers exhibit mixed responses to CO2-induced ocean acidification. Geol. 37:1131–1134.

Rilov, G. 2016. Predator-prey interactions of marine invaders. In: Rilov, G. & A. J. Crooks, editors. Biological invasions in marine ecosystems. Berlin, Germany: Springer. pp. 261–285.

Roddreger-Romero, A., N. Jimenez-Tenorio, M. D. Basallote, M. R. De Orte, J. Blasco & I. Riba. 2014. Predicting the impacts of CO2 leakage from subseabed storage: effects of metal accumulation and toxicity on the model benthic organism Rideptes philippinarum. Environ. Sci. Technol. 48:12292–12301.

Rosenthal, R. 1979. The “file drawer problem” and tolerance for null results. Psychol. Bull. 85:638–641.

Ross, P. M., L. Parker & M. Byrne. 2016. Transgenerational responses of molluscs and echinoderms to changing ocean conditions. ICES J. Mar. Sci. 73:537–549.

Schalkhauser, B., C. Bock, K. Stemmer, T. Brei, H.-O. Pörtner & G. Lannig. 2013. Impact of ocean acidification on escape performance of the king scallop, Pecten maximus, from Norway. Mar. Biol. 160:1995–2006.

Schneider, C. A., W. S. Rasband & K. W. Eliceiri. 2012. NIH Image to ImageJ: 25 years of image analysis. Nat. Methods 9:671–675.

Schrøder, J. B., K. M. Schoenrock, J. B. McClintock, C. D. Amrsk & R. A. Angus. 2014. Multiple stressor effects of near-future elevated seawater temperature and decreased pH on righting and escape behaviors of two common Antarctic gastropods. J. Exp. Mar. Biol. Ecol. 457:90–96.

Spad, B. L., P. L. Munday & S.-A. Watson. 2018. Predatory strategies and behaviours in echelopods are altered by elevated CO2. Glob. Chang. Biol. 24:2585–2596.

Spad, B. L., S.-A. Watson, J. T. Chase & P. L. Munday. 2014. Projected near-future CO2 levels increase activity and alter defensive behaviours in the tropical squid Idiosepius pygmaeus. Biol. Open 3:1063–1070.

Spad, B. L., J. van de Koppel, M. D. Bertness, L. E. Stanton & I. A. Mendelsohn. 2005. Drought, snails, and large-scale die-off of southern US salt marshes. Science 310:1803–1806.

Spad, B. L. & M. D. Bertness. 2002. A trophic cascade regulates salt marsh primary production. Proc. Natl. Acad. Sci. USA 99:10500–10505.

Sunday, J. M., P. Calosi, S. Dupont, P. L. Munday, J. H. Stillmon & T. B. Reusch. 2014. Evolution in an acidifying ocean. Trends Ecol. Evol. 29:117–125.

Sweeney, K., B. Cusack, F. Armagost, T. O'Brien, C. N. Keiser & J. N. Pruitt. 2013. Predator and prey activity levels jointly influence the outcome of long-term foraging bouts. Behav. Ecol. 24:1205–1210.

Tallqvist, M. 2001. Burrowing behaviour of the Baltic clam Macoma baltica: effects of sediment type, hypoxia and predator presence. Mar. Ecol. Prog. Ser. 212:183–191.

Thomsen, J., L. S. Stapp, K. Hayhert, H. Schade, M. Danelli, G. Lannig, K. M. Wegner & F. Melzner. 2017. Naturally acidified habitat selects for ocean acidification-tolerant mussels. Sci. Adv. 3:e1602411.

Tresguerres, M. & T. J. M. Richardson. 2017. Acid–base physiology, neurobiology and behaviour in relation to CO2-induced ocean acidification. J. Exp. Biol. 220:2136–2148.

Vargas, C.A., N.A. Lagos, M.A. Lardies, C. Duarte, P.H. Manriquez, V.M. Aguilera, B. Broitman, S. Widdicombe & S. Dupont. 2017. Species-specific responses to ocean acidification should account for local adaptation and adaptive plasticity. Nat. Ecol. Evol. 1:84.

Viechhauer, W. 2010. Conducting meta-analyses in R with the metafor package. J. Stat. Softw. 36:1–48.
Viechtbauer, W. 2017. metafor: meta-analysis package for R. Available at: https://cran.r-project.org/web/packages/metafor/index.html.

Waldbusser, G. G. & J. E. Salisbury. 2014. Ocean acidification in the coastal zone from an organism’s perspective: multiple system parameters, frequency domains, and habitats. *Annu. Rev. Mar. Sci.* 6:221–247.

Wallace, R. B., H. Baumann, J. S. Grear, R. C. Aller & C. J. Gobler. 2014. Coastal ocean acidification: the other eutrophication problem. *Estuar. Coast. Shelf Sci.* 148:1–13.

Walsh, S. 2018. Effects of ocean acidification on respiration and burrowing behaviour of infaunal marine invertebrates in the Bay of Fundy. BSc thesis, University of New Brunswick, Saint John, Canada.

Watson, S.-A., J. B. Fields & P. L. Munday. 2017. Ocean acidification alters predator behaviour and reduces predation rate. *Biol. Lett.* 13:20160797.

Watson, S.-A., S. Lefevre, M. I. McCormick, P. Domenici, G. E. Nilsson & P. L. Munday. 2014. Marine mollusc predator-escape behaviour altered by near-future carbon dioxide levels. *Proc. Biol. Sci.* 281:20132377.

Welch, M. J. & P. L. Munday. 2017. Heritability of behavioural tolerance to high CO$_2$ in a coral reef fish is masked by nonadaptive phenotypic plasticity. *Evol. Appl.* 10:682–693.

Welch, M. J., S.-A. Watson, J. Q. Welsh, M. I. McCormick & P. L. Munday. 2014. Effects of elevated CO$_2$ on fish behaviour undiminished by transgenerational acclimation. *Nat. Clim. Chang.* 4:1086–1089.

Whittman, A. C. & H.-O. Pörtner. 2013. Sensitivities of extant animal taxa to ocean acidification. *Nat. Clim. Chang.* 3:995–1001.

WHOI. 2012. The chemistry of ocean acidification [online]. Available at: http://www.whoi.edu/OCB-OA/page.do?pid=112136. Accessed September 21, 2018.

Wong, B. B. M. & U. Candolin. 2015. Behavioral responses to changing environments. *Behav. Ecol.* 26:665–673.

Zakroff, C., T. A. Mooney & C. Wirth. 2018. Ocean acidification responses in paralarval squid swimming behavior using a novel 3D tracking system. *Hydrobiologia* 808:83–106.

Zhang, H., S. G. Cheung & P. K. S. Shin. 2014. The larvae of congenic gastropods showed differential responses to the combined effects of ocean acidification, temperature and salinity. *Mar. Pollut. Bull.* 79:39–46.

Zittier, Z. M., T. Hirse & H.-O. Pörtner. 2013. The synergistic effects of increasing temperature and CO$_2$ levels on activity capacity and acid–base balance in the spider crab, *Hyas araneus*. *Mar. Biol.* 160:2049–2062.