Behavioural Stress Propagation in Benthic Invertebrates Caused by Acute pH Drop-Induced Metabolites

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Studies on pH stress in marine animals typically focus on direct or species-specific aspects. We here test the hypothesis that a drop to pH = 7.6 indirectly affects the intra- and interspecific interactions of benthic invertebrates by means of chemical communication. We recorded fitness-relevant behaviours of small hermit crabs *Diogenes pugilator*, green shore crabs *Carcinus maenas*, and harbour ragworms *Hediste diversicolor* in response to short-term pH drop, and to putative stress metabolites released by conspecifics or gilt-head sea bream *Sparus aurata* during 30 min of acute pH drop. Not only did acute pH drop itself impair time to find a food cue in small hermit crabs and burrowing in harbour ragworms, but similar effects were observed under exposure to pH drop-induced stress metabolites. Stress metabolites from *S. aurata*, but not its regular control metabolites, also induced avoidance responses in all recipient species. Here, we confirm that a short-term abrupt pH drop, an abiotic stressor, has the capacity to trigger the release of metabolites which induce behavioural responses in conspecific and heterospecific individuals, which can be interpreted as a behavioural cost. Our findings that stress responses can be indirectly propagated through means of chemical communication warrant further research to confirm the effect size of the behavioural impairments caused by stress metabolites and to characterise their chemical nature.

**Keywords:** behavioural cost, stress propagation, stress metabolites, chemical communication, ocean acidification

**INTRODUCTION**

Compared to the open ocean, coastal areas, and particularly intertidal zones are highly variable environments characterised by abrupt changes in water parameters. This includes fluctuations in pH beyond 0.3 units, the levels predicted for average change related to the process of ocean acidification toward the end of the century (Caldeira and Wickett, 2003; Sabine et al., 2004; IPCC, 2019). While this may mean that intertidal species are more resilient to climate change due to their acquired tolerances of pH fluctuations, it also forces them to live more frequently near their physiological tolerance limits (Truchot and Duhamel-Jouve, 1980; Hofmann et al., 2011; Sokolova, 2018; Wolfe et al., 2020). Superimposing ocean acidification on natural pH fluctuations may further increase the variability of organisms' responses (Eriander et al., 2015). Therefore, organisms...
inhabiting intertidal areas are interesting models to study the effects of short-term pH fluctuations within the IPCC predicted range. A low environmental pH can directly alter animal behaviour through several pathways, which include (i) deviation of energy budgets toward the stress response (Pörtner, 2008), (ii) fleeing to avoid the sources of stress (Pörtner and Peck, 2010; Abreu et al., 2016), (iii) disrupted information detection and processing leading to impaired decision-making (Briffa et al., 2012; Porteus et al., 2018; Thomas et al., 2020; Cothran et al., 2021), and (iv) alteration of the chemical signals themselves impacting the sensory environment and the transfer of information (Wyatt et al., 2014; Roggatz et al., 2016, 2019). Behavioural effects triggered by lowered pH are known to occur in different taxonomic groups such as crustaceans (de la Haye et al., 2011), marine ragworms (Bond, 2018), and fish (Munday et al., 2009), although recent research debates both their ubiquitousness and effect size (Clark et al., 2020a; Clements et al., 2020a,b, but see Clark et al., 2020b; Munday et al., 2020; Williamson et al., 2021 for the importance of which comparisons are made). In addition, it should be mentioned that although there is little literature disentangling the behavioural effects of pH drop vs. high CO₂, an increasing body of recent research evidenced the role of pH-dependent altered chemical communication (Roggatz et al., 2016; Schirrmacher et al., 2020; Porteus et al., 2021; Velez et al., 2021).

In aquatic environments, where visibility can be limited, infochemicals and chemo-sensory functions, such as pheromones used for mating (Karlsen and Lüscher, 1959) are crucial for communication (Hardege, 1999; Jordão and Volpato, 2000; Ashur et al., 2017; Saha et al., 2019). However, infochemicals are also a mechanism to signal stress—but stress communication has mostly been researched within the context of biotic stressors. For example, alarm cues released following mechanical damage from fish epidermal club cells can trigger panic reactions in conspecifics and heterospecifics (Toa et al., 2004; Júnior et al., 2010). Such mechanisms of chemical communication also occur in invertebrates, as evidenced by the reduced out-of-burrow activity of the marine polychaete Alitta virens exposed to damaged conspecifics (Watson et al., 2005; Ende et al., 2017). Disturbance cues refer to chemicals that may be stored in gill epithelium or urine, and are released voluntarily or involuntarily by disturbed or stressed prey, to induce early antipredator responses in recipients to anticipate potential threats (Bairos-Novak et al., 2017; Goldman et al., 2020a). The central role of chemical communication in the aquatic environment and the recent evidence of its impairment by ocean acidification pinpoints the need for a deeper understanding of such potential environmental modulation of chemical signalling (Chivers et al., 2013).

Overall, though, it is not well understood yet whether abiotic stressors such as pH drop can also induce the release of chemical cues and whether these can propagate the stress response to other individuals. For such cues, we here introduce the term “stress metabolites” as defining such compounds released, voluntarily or not, by an organism in response to abiotic stressors. These can be detected and processed by conspecifics and/or heterospecifics, leading to the induction of a behavioural stress response (Hazlett, 1985). Of note, Draper and Weissburg (2019) defined the “direct effects” of elevated CO₂ on predator-prey interactions as the effects modifying the sensory pathways (cue production and emission by the donor and cue reception and processing by the receiver). Here, we term the effects of acute pH drop as “direct” when the animal is exposed to the stressor itself and as “indirect” when the animal is exposed to the stress metabolites released upon pH stress. Both direct and indirect effects may be guided by sensory pathways as well as metabolism in senders and receivers (as defined in Draper and Weissburg, 2019). We term “stress propagation” the signalling of stress responses within or between species by means of stress metabolites (Figure 1A). Detecting stress metabolites may allow other individuals to modify their behaviour to avoid a change in the abiotic environment, and communities to coordinate or potentiate their response to ensure survival (Mothersill et al., 2007; Giaconini et al., 2015; Abreu et al., 2016). However, to investigate the function of any pH drop-induced chemical cues, the original stressor (pH drop) must first be removed from the experimental design.

In this study, we investigate, within and among species inhabiting the intertidal zone, the indirect effects of acute pH drop through stress metabolites induced by it on fitness-relevant behaviours. Using a full factorial design, we test the hypothesis that an acute pH drop to end-of-century level (7.6) will both directly (i.e., when the animal is exposed to the abiotic stressor) and indirectly (i.e., when the animal is exposed to the stress metabolites) affect behaviour through the induction of stress metabolites. We observe three marine invertebrates (small hermit crab Diogenes pugilator, green shore crab Carcinus maenas, and harbour ragworm Hediste diversicolor) exposed to control pH and pH drop in combination with conditioned water from both conspecifics and their potential vertebrate predator, the gilt-head sea bream S. aurata.

**MATERIALS AND METHODS**

**Experimental Design**

Small hermit crabs Diogenes pugilator and green shore crabs Carcinus maenas were collected in autumn at low tide in the Ria Formosa lagoon (Portugal). Harbour ragworms (Hediste diversicolor) were sourced via a local supplier (Valbaits) from the Setubal lagoon (Portugal). Animals were acclimated for 1 week at pH 8.1 (pH is reported using National Bureau of Standards scale) in large flow-through open-circuit communal tanks (continuous flow of 0.05 L/min) mimicking natural habitats at the Ramalhete Marine Station (CCMAR, Faro, Portugal) in a direct CO₂-controlled system (described in Sordo et al., 2016, 2018; Gregório et al., 2019) with pCO₂ constantly measured and adjusted. Two system seawater conditions were used, either control pH of 8.1 ± 0.015 or pH drop of 7.6 ± 0.008. For a measured total alkalinity of 2,500 µmol/kg SW, the pCO₂ was calculated as 537 and 1,922 µatm in the control and pH drop system water, respectively, according to the CO₂calc software (v1.2.0, Robbins et al., 2010). pCO₂ was not estimated in any treatment containing reef buffer, HCl, or dilutions, as total alkalinity was not measured.
FIGURE 1 | (A) Concept of stress propagation from pH-stressed donors to naive receivers, themselves stressed by metabolites released by the donors. Solid lines and black flash symbols represent direct pH drop effects. Dashed lines and white flash symbols represent indirect pH drop effects mediated by stress metabolites (circles) released by conspecifics (black lines) or heterospecifics (grey lines). (B) Schematic experimental design showing the presence vs. absence of predictors (pH drop, stress metabolites, donor). Behavioural effects of short-term acute pH drop and stress metabolites it induced were tested in three species: Diogenes pugilator, Carcinus maenas, and Hediste diversicolor. Metabolites were obtained by conditioning donors in either control pH = 8.1 (releasing putative control metabolites), or pH drop = 7.6 (releasing putative stress metabolites), followed by pH adjustments for factorial design yielding four experimental conditions CM, pH drop, SM, and pH drop + SM. Predictors are binary coded as 0 (control metabolites, control pH) and 1 (stress metabolites, pH drop). Metabolites originated from conspecifics or the heterospecific Sparus aurata. Behaviour assays for crabs consisted in locating a feeding cue in 300 s. Specimens of H. diversicolor were placed on top of sediment and burrowing behaviour was recorded for 300 s. A range of avoidance behaviours were also recorded. Experimental conditions were CM, control metabolites in control pH; SM, control metabolites in pH drop; pH drop, control metabolites in pH drop; pH drop + SM, stress metabolites in pH drop. Animal drawings by A. Murcia and KOW.

in those, and pCO₂ could therefore have differed from that in the system water (see Supplementary Information for details). Seawater parameters were measured daily at 2.30 pm (mean temperature: 20.16°C ± 1.05°C, mean salinity: 35.67 PSU ± 0.26 PSU, mean dissolved oxygen: 7.55 mg/L ± 0.16 mg/L). A total pool of approx. 100–120 D. pugilator, 150–200 C. maenas, and over 150 H. diversicolor was used during the experimental period, yielding a total of 921 observations. Because no individual marking could be achieved, we aimed to space out the reuse of animals in successive behavioural assays by circulating animals through recovery tanks afterward, before returning them to their stock population tanks once a day. Animal reuse was randomised across treatments and treatments randomised per day to prevent any confounding effects on the measured behaviours. All experiments were conducted in October 2019, except one independent set of observations (n = 40) in C. maenas conducted in September 2018, which was analysed together with the 2019 data with the year treated as a covariate.

A three-way factorial design of pH drop × stress metabolites × donor species was generated to study the effects of acute pH drop, stress metabolites induced by it, and their combination vs. a control containing regular metabolites (control metabolites) (Figure 1B). Metabolite donor species were D. pugilator, C. maenas, and H. diversicolor (called conspecific donors), and the potential predator Sparus aurata (called heterospecific donor). Metabolite donors were conditioned for 30 min in seawater at regular pH (pH 8.1, 538 μatm CO₂, putatively inducing control metabolite release), or pH drop (pH 7.6, 1,922 μatm CO₂, putatively inducing stress metabolite release). Recipient species were D. pugilator, C. maenas, and H. diversicolor which received water containing either conspecific or heterospecific metabolites. To achieve the full factorial design, recipient species received either control or stress metabolites and were tested in either control pH (8.1) or pH drop (7.6), by re-adjusting the pH of the conditioned water before each bioassay (with the pH verified with an accuracy of 0.02 units using a portable pH metre). Overall, four different experimental treatments were obtained: (i) putative control metabolites at pH 8.1 (CM), (ii) putative control metabolites at pH 7.6 (pH drop), (iii) putative stress metabolites at pH 8.1 (SM), (iv) and putative stress metabolites at pH 7.6 (pH drop + SM). Testing conspecific and heterospecific metabolites with three recipient species amounted to a total of 12 treatments. Prior to use in recipient species, conditioned seawater from H. diversicolor and S. aurata (0.0067 fish/L) was 10-fold diluted in fresh system seawater at the desired pH. To explore the possibility that stress metabolites are equivalent to highly concentrated control metabolites, we additionally tested the effects of undiluted S. aurata control metabolites at pH 8.1 in H. diversicolor and D. pugilator. See Supplementary Information for further details on treatments (Supplementary Table 1) and water conditioning (Supplementary Methods).

Behavioural Bioassays
For each of the four conditions, we measured the time to find a feeding cue (1/10 diluted mussel juice) vs. a mock (seawater) cue in D. pugilator and C. maenas, or to bury the
head entirely in the sand in *H. diversicolor*, and dubbed this variable “time-to-success.” Behavioural assays were terminated once the animal successfully grabbed the ballasted sponge containing the feeding cue with their pincers (*D. pugilator* and *C. maenas*) or buried its entire head (*H. diversicolor*), or at a maximum time of 300 s. Both feeding and burrowing behaviours are tested response variables in crabs (de la Haye et al., 2012; Wang et al., 2018) and ragworm (Bhuiyan et al., 2021) exposed to pH drop. Additionally, avoidance behaviour was binary coded. In *D. pugilator* and *C. maenas*, these avoidance behaviours included freezing (suddenly retreating into the shell or attempting to burrow, sudden and lasting arrest in locomotion for at least 120 consecutive seconds or more than 150 s in total), and escaping (walking along the walls or retreating into a corner of the tank for at least 120 consecutive seconds or more than 150 s in total). Such freeze and escape behaviours indicate danger in crustaceans (Katz and Rittschof, 1993; Perrot-Minnot et al., 2017; Tomić et al., 2017). In *H. diversicolor*, avoidance behaviours consisted of freezing, which might be accompanied by spread of jaws, sideways-undulating behaviour, and formation of a noticeable slime cap whilst outside the sediment. These behaviours indicate extreme stress in marine polychaetes (Mouneyrac et al., 2003; Burlinson and Lawrence, 2007; McBriarty et al., 2018). The feeding cues were randomly assigned left or right to the crabs. See Supplementary Methods for further details on behavioural assays. All data is given as Supplementary Dataset.

**Statistical Analysis**

Avoidance behaviours were analysed using generalised linear models for logit regression with binomial distribution using the *stats* R package (R Core Team, 2020). Time-to-success was
## Results of Cox proportional hazard model for the main effects of predictors (pH drop, stress metabolites, donor) on the time-to-success analysis in small hermit crab (*D. pugilator*, *n* = 320 observations with 120 events of finding a food cue, degrees of freedom = 312), green shore crab (*C. maenas*, *n* = 198 observations with 122 events of finding a food cue, degrees of freedom = 181), and harbour ragworm (*H. diversicolor*, *n* = 325 observations with 234 events of burrowing head in sediment, degrees of freedom = 317).

| Predictors | Success (hazard ratio) | Estimate | SE | Z | P  |
|------------|------------------------|----------|----|---|----|
| **D. pugilator** |                      |          |    |   |    |
| pH drop    | 0.4702                 | −0.7546  | 0.3530 | −2.1378 | 0.0325 |
| Stress metabolites | 0.8106             | −0.2100  | 0.3167 | −0.6631 | 0.5073 |
| Donor      | 0.3460                 | −1.0613  | 0.3843 | −2.7613 | 0.0058 |
| pH drop:stress metabolites | 1.7878      | 0.5810   | 0.4858 | 1.1959 | 0.2317 |
| pH drop:donor | 3.2842           | 1.1891   | 0.6441 | 2.1853 | 0.0289 |
| Stress metabolites:donor | 1.4970       | 0.4034   | 0.5326 | 0.7575 | 0.4487 |
| pH drop:stress metabolites:donor | 0.4168   | −0.8752  | 0.7498 | 1.1672 | 0.2431 |
| **C. maenas** |                      |          |    |   |    |
| pH drop    | 0.7490                 | −0.2890  | 0.3620 | −0.7982 | 0.4247 |
| Stress metabolites | 1.2156            | 0.1953   | 0.2887 | 0.6762 | 0.4899 |
| Donor      | 1.4445                 | 0.3678   | 0.3385 | 1.0865 | 0.2773 |
| pH drop:stress metabolite | 0.8674       | −0.1422  | 0.4630 | −0.3072 | 0.7587 |
| pH drop:donor | 0.2870            | −1.2484  | 0.6312 | −1.9777 | 0.0480 |
| Stress metabolites:donor | 0.2981       | −1.2102  | 0.5008 | −2.4165 | 0.0157 |
| pH drop:stress metabolites:donor | 6.0273 | 1.7963   | 0.8261 | 2.1743 | 0.0297 |
| **H. diversicolor** |                      |          |    |   |    |
| pH drop    | 0.3043                 | −1.1899  | 0.3045 | −3.9075 | < 0.0001 |
| Stress metabolites | 0.3520            | −1.0442  | 0.3049 | −3.4251 | 0.0006 |
| Donor      | 0.6965                 | −0.3616  | 0.2258 | −1.6013 | 0.1093 |
| pH drop:stress metabolites | 3.9914       | 1.3841   | 0.4411 | 3.1376 | 0.0017 |
| pH drop:donor | 2.4669            | 0.9030   | 0.3816 | 2.3663 | 0.0180 |
| Stress metabolites:donor | 1.7318       | 0.5492   | 0.3816 | 1.4390 | 0.1501 |
| pH drop:stress metabolites:donor | 0.2291     | −1.4736  | 0.5633 | −2.6158 | 0.0089 |

Unsuccessful observations are censored. Significance (*P* ≤ 0.05) is shown by *p*-values in bold. Overall significance of the models using Likelihood ratio tests were: *D. pugilator*: *P* = 0.06; *C. maenas*: *P* = 0.009; *H. diversicolor*: *P* < 0.0001; Covariates were dropped from models after analyses of deviance showed that they passed the Chi-squared test (*D. pugilator*: number of water uses: *P* = 0.1163, crab size: *P* = 0.6318; *C. maenas*: number of water uses: *P* = 0.6104, crab size: *P* = 0.9995, year: *P* = 0.3348; *H. diversicolor*: number of water uses: *P* = 0.2649). Success ratio (aka hazard ratio) is the exponentiated estimate. SE is the standard error of estimate.

Modelled for the time to reach a feeding cue in *D. pugilator* and *C. maenas* or to burrow the head in *H. diversicolor* depending on the three predictors: pH drop, stress metabolites, and donor. Time-to-success data was analysed with a time-to-event analysis (also called survival analysis) using Cox proportional hazard models from the *survival* R package (Therneau and Grambsch, 2000; Therneau, 2021). The event being the success of food cue location (in crabs) or burrowing the head in sediment (in worms), the analysis was hereafter referred to as "time-to-success analysis." The exponentiated estimates (hazard ratios) from the Cox proportional hazard models were expressed as "success ratio." Success ratios were visualised using the `plot_model` function from the `sjPlot` R package (Lüdecke, 2021). The "success probability" (the probability of the feeding or burrowing event occurring at any time over 300 s) over time was represented by Kaplan-Meier curves drawn using the `survminer` R package (Kassambara et al., 2020). Animals not reaching the feeding cue or not burying their head were censored and assigned the maximum time of "300+".

All statistical models always included the main effects and interaction terms of the binary predictors: pH drop (pH = 8.1 vs. pH = 7.6), stress metabolites (stress metabolites vs. control metabolites), and donor (conspecific vs. heterospecific). Covariates (year, number of water uses, crab size, where relevant; see section 2.2 in Supplementary Information) were excluded from models when deemed insignificant compared to the null model by at least two model selection methods among the following: an ANOVA Chi-square test from the `stats` R package (R Core Team, 2020), the Akaikes Information Criterion (ΔAIC), and Bayesian Information Criterion (BIC) from the `AICcmodavg` R package (Mazerolle, 2020). Overall model fit *p*-values were retrieved from the ANOVA Chi-squared test or the Likelihood ratio test for generalised linear models and Cox-proportional models, respectively. Pairwise comparisons between treatments involved in the interaction term between the three predictors were obtained from statistical models using the `emmeans` R package (Lenth, 2021), wherein false discovery rate *p*-value adjustments were applied for post hoc term-wide multiple testing.

To investigate the possibility that stress metabolites are equivalent to highly concentrated control metabolites (which were present in CM and pH drop treatments but in 10-fold dilution), additional tests compared the behavioural response of *D. pugilator* and *H. diversicolor* to 10-fold diluted stress metabolites and control metabolites to that of undiluted control metabolites from *S. aurata* (see Supplementary Information,
section 2.4). The full dataset may include animals tested at most twice over the course of the experimental period. We therefore performed random bootstrapping of 50% of the dataset (Supplementary Information, section 2.5). All statistical analyses were conducted in RStudio (R Studio Team, 2020) with a significance threshold of $P \leq 0.05$. See R script and Supplementary Information for further details.

RESULTS

Response of Small Hermit Crab Diogenes pugilator to pH, Stress Metabolite, and Donor Predictors

The time-to-success analysis was not conclusive for the stress metabolite predator in D. pugilator (Figure 2A and Table 1, $Z = -0.66, P = 0.5073$). On the other hand, the Cox proportional hazard model (overall Likelihood ratio test model fit: $P = 0.06$) found that both pH drop (feeding success ratio $= 0.47, Z = -2.14, P = 0.0325$) and metabolites from S. aurata (feeding success ratio $= 0.35, Z = -2.76, P = 0.0058$) had significant negative effects on the feeding success ratio of D. pugilator. In addition, there was a significant interaction between pH drop and metabolite donor terms on the feeding success of D. pugilator ($Z = 2.19, P = 0.0289$). Overall, pH drop induced a significantly lower success (risk) score in the conspecific treatment (Figure 2B). Post hoc analyses evidenced that all treatments (CM, pH drop, SM, and pH drop + SM) induced similar feeding time responses in both the conspecific and heterospecific donor groups (Supplementary Table 2).

Avoidance responses of D. pugilator did not depend on pH drop ($Z = 0.25, P = 0.8049$) nor on stress metabolites ($Z = -0.25, P = 0.7995$), overall Chi-square test model fit: $P < 0.0001$ (Table 2), but were significantly more pronounced when metabolites originated from S. aurata (69%) instead of conspecifics (26%, $Z = 2.46, P = 0.0139$, Figure 3 and Table 2). After splitting the display of avoidance behaviour by donor, pairwise comparisons failed to find differences between the four treatments (CM, pH drop, SM, and pH drop + SM), but confirmed that the donor effect existed across all four treatments (Supplementary Table 3 and Figure 3). However, partitioning the avoidance behaviour of D. pugilator into freezing and escaping responses evidenced that escaping significantly increased with S. aurata control metabolites only when tested in pH drop (Supplementary Figures 1, 2 and Supplementary Tables 4–7, see Supplementary Results).

Response of Green Shore Crab Carcinus maenas to pH, Stress Metabolite, and Donor Predictors

The Cox proportional hazard model (overall Likelihood ratio test model fit: $P = 0.009$) showed that the feeding success ratio of C. maenas did not significantly vary with pH ($Z = -0.80, P = 0.4247$), metabolites ($Z = 0.68, P = 0.4989$), nor donor ($Z = 1.09, P = 0.2773$) terms (Figure 2 and Table 1). Nevertheless, the interaction terms were significant. Post hoc tests revealed that time-to-success responses were similar across treatments CM, pH drop, SM, and pH drop + SM when C. maenas received conspecific metabolites (Supplementary Table 8). This pattern changed when S. aurata was the metabolite donor as evidenced by significantly lower feeding success scores in C. maenas exposed to pH drop ($Z = 2.97, P = 0.0179$), SM ($Z = 2.48, P = 0.0394$), and the trend for pH drop + SM ($Z = 2.20, P = 0.0563$), compared to the control CM.

| Predictors               | Estimate | SE     | Z      | P     |
|-------------------------|----------|--------|--------|-------|
| D. pugilator (Intercept) | -0.9694  | 0.3541 | -2.7380| 0.0062|
| pH drop                 | 0.1221   | 0.4944 | 0.2470 | 0.8049|
| Stress metabolites      | -0.1292  | 0.5086 | -0.2540| 0.7995|
| Donor                   | 1.1701   | 0.4758 | 2.4590 | 0.0139|
| pH drop:stress metabolites| -0.2603  | 0.7219 | -0.3610| 0.7185|
| pH drop:donor           | 0.7758   | 0.6919 | 1.1210 | 0.2622|
| Stress metabolites:donor| 1.0272   | 0.7022 | 1.4830 | 0.1435|
| pH drop:stress metabolites:donor | -0.8890 | 1.0039 | -0.8860| 0.3759|

| C. maenas (Intercept)   | -0.2224  | 0.6725 | -0.3307| 0.7409|
| pH drop                 | -1.1263  | 0.9173 | -1.2279| 0.2195|
| Stress metabolites      | -1.1263  | 0.9173 | -1.2279| 0.2195|
| Donor                   | -0.4626  | 0.8326 | -0.5556| 0.5785|
| Number of water uses    | -0.3077  | 0.1566 | -1.9772| 0.0480|
| pH drop:stress metabolites| 2.2527   | 1.2978 | 1.7357 | 0.0826|
| pH drop:donor           | 5.5551   | 1.5992 | 3.6090 | 0.0003|
| Stress metabolites:donor| 3.8799   | 1.2465 | 3.1127 | 0.0019|
| pH drop:stress metabolites:donor | -7.5415 | 1.9329 | -3.9017| 0.0001|

| H. diversicolor Model 1 (both donors) (Intercept) | 0.2801 | 0.3790 | 0.7391 | 0.4598|
| Donor                                               | 1.0944 | 0.3169 | 3.4554 | 0.0006|
| Number of water uses                                 | -0.7745| 0.1462 | -5.2980| <0.0001|

| H. diversicolor Model 2 (S. aurata donor) (Intercept) | -0.6931 | 0.5000 | -1.3863| 0.1657|
| pH drop                                             | -18.8729| 1603.1137| -0.0118| 0.9906|
| Stress metabolites                                   | 3.3557 | 0.7788 | 4.3086 | <0.0001|
| pH drop:stress metabolites                          | 16.2548| 1603.1138| 0.0101 | 0.9919|

Due to missing observations in conspecific control metabolites at control pH in Hediste diversicolor, data was analysed with two models. Model 1: effect of donor across all treatments (sample size: 253 observations). Model 2: effects of pH and metabolites in subset receiving S. aurata metabolites (sample size: 154 observations). Overall significance of models from Chi-squared analyses of deviance when including only predictors were: D. pugilator: $P < 0.0001$; C. maenas: $P < 0.0001$; H. diversicolor: $P < 0.0001$ (model 1) and $P < 0.0001$ (model 2). Covariates were dropped from models after analyses of deviance showed that they passed the Chi-squared test (D. pugilator: number of water uses: $P = 0.5963$, crab size: $P = 0.9158$; C. maenas: crab size: $P = 0.2710$). Significance ($P \leq 0.05$) is shown by $p$-values in bold. SE is the standard error of estimate.
In *C. maenas*, the predictors pH drop \((Z = -1.23, P = 0.2195)\), stress metabolites \((Z = -1.23, P = 0.2195)\), and donor \((Z = -0.56, P = 0.5785)\) did not alter avoidance responses but their interaction terms were significant (overall Chi-square test model fit: \(P < 0.0001\), Table 2 and Figure 3). Pairwise comparisons showed no differences between the four treatments (CM, pH drop, SM, pH drop + SM) in avoidance patterns of *C. maenas* receiving conspecific metabolites. Conversely, *C. maenas* facing *S. aurata* metabolites while experiencing treatments of pH drop (94%, \(Z = -3.60, P = 0.0020\)), SM (75%, \(Z = -3.28, P = 0.0031\)), and pH drop + SM (56%, \(Z = -2.33, P = 0.04\)) significantly increased their avoidance display compared to control CM (18%). Moreover, pH drop combined with stress metabolites (pH drop + SM treatment) instead of control metabolites (pH drop treatment) significantly lowered avoidance behaviours (\(Z = 2.21, P = 0.0405\), Supplementary Table 9 and Figure 3). Partitioning the avoidance behaviour of *C. maenas* into freezing and escaping responses evidenced that escaping explained the avoidance response whereas no clear patterns were observed in the freezing behaviour (Supplementary Figures 1, 2 and Supplementary Tables 10–13, see Supplementary Results).

### Response of Harbour Ragworm *Hediste diversicolor* to pH, Stress Metabolite, and Donor Predictors

Burrowing success responses of *H. diversicolor* did not depend on the donor species \((P = 0.1093\), Figure 2 and Table 1\). However, the Cox proportional hazard model (overall Likelihood ratio test model fit: \(P < 0.0001\)) evidenced that both pH drop (burrowing success ratio \(= 0.30, Z = -3.91, P < 0.0001\)) and stress metabolites (burrowing success ratio \(= 0.35, Z = -3.42, P = 0.0006\)) terms significantly altered burrowing time responses of *H. diversicolor*. Significant interactions between the main predictors required to decipher the involvement of within-donor treatment effects (Supplementary Table 14). Post hoc tests revealed that pH drop \((Z = 3.91, P = 0.0006)\), SM \((Z = 3.43, P = 0.0012)\), and pH drop + SM \((Z = 3.47, P = 0.0012)\) treatments significantly lowered burrowing success scores compared to the control CM in *H. diversicolor* exposed to conspecific metabolites. Moreover, *H. diversicolor* facing *S. aurata* metabolites had lower burrowing success scores in the pH drop + SM treatment compared to the control CM \((Z = 3.35, P = 0.0049)\).

*H. diversicolor* displayed more avoidance in response to *S. aurata* metabolites (47%) compared to conspecific metabolites (20%, \(Z = 1.09, P = 0.0006\), overall Chi-square test model fit: \(P < 0.0001\), Table 2 and Figure 3). *H. diversicolor* exposed to *S. aurata* metabolites were not affected by pH drop \((Z = -0.01, P = 0.9906)\) whereas stress metabolites induced significantly more avoidance than control metabolites \((Z = 4.31, P < 0.0001)\), overall Chi-square test model fit: \(P < 0.0001\), Table 2\). There were no differences across pH drop, SM, and pH drop + SM treatments in *H. diversicolor* receiving conspecific metabolites (Supplementary Table 15). Pairwise comparisons revealed that the SM treatment (93%) triggered significantly more avoidance than CM (33%, \(Z = -4.31, P = 0.0001\)) and pH drop + SM treatments (51%, \(Z = 3.92, P = 0.0003)\)). Specimens of *H. diversicolor* exposed to *S. aurata* metabolites displayed different avoidance responses in the control treatment CM (Supplementary Video 1) compared to pH drop (slow-down burrowing response, Supplementary Video 2), SM (sideways-undulating behaviour with body flips), Supplementary Video 3, and pH drop + SM (raised head and spread mouth parts with freezing behaviour in Supplementary Video 4 and slow-down movement with sideways undulating behaviour in Supplementary Video 5).

Importantly, the behavioural responses of *H. diversicolor* and *D. pugilator* remained unchanged even when we used undiluted control metabolites (see Supplementary Information, section 2.4, Supplementary Figure 3 and Supplementary Tables 16, 17). Of note, the avoidance response of *H. diversicolor* and *D. pugilator* faded as water was reused (Supplementary Information, section 2.2, Supplementary Figure 4).

Furthermore, random bootstrapping of 50% of the dataset (Supplementary Information, section 2.5, Supplementary Figure 5 and Supplementary Table 20) did not change the outcome of time-to-event analysis for any species.

### DISCUSSION

#### Direct Effects of pH Drop and Donor Type on Assay Success and Avoidance Behaviours

In this study, we performed over 900 behavioural observations, and our results show species-specific responses, donor-dependent effects, as well as sometimes large within-treatment variability. *Sparus aurata*-conditioned water, whether it contained control metabolites or pH stress-induced metabolites, elicited avoidance in all recipient species which can be attributed to antipredator behaviours. Despite the donor effect, however, much of the behavioural variance was explained by the effects of pH drop and stress metabolites, their interaction, or their interaction with the donor term (Figure 2).

We found that pH drop lowered success ratios in feeding and burrowing in *Diogenes pugilator* and *Hediste diversicolor*, respectively. Such low pH-induced impairments of fitness-relevant behaviours were previously found in hermit crabs *Pagurus bernhardus* and *P. tanneri* as well as in the Japanese stone crab *Charybdis japonica* and may indicate impaired decision-making (de la Haye et al., 2011, 2012; Kim et al., 2015; Wu et al., 2017). Past literature also reported delayed burrowing responses in the harbour ragworm *H. diversicolor* exposed for 28 days to pH drop (Bhuiyan et al., 2021), and an inverse relationship between burrowing and pH in the king ragworm *Alitta virens* (Batten and Bamber, 1996). These behavioural alterations may reflect the cost of acid-base regulation to counteract hypercapnia (Pörtner, 2008), as marine ragworms overexpress the acid-base regulator *Carbonic Anhydrase* (CA) at the expense of energy reserves in response to acidification (Freitas et al., 2016; Wage et al., 2016). In the longer term, behavioural costs of an altered burrowing activity may extend to crucial ecological functions as shown by the diminished bioturbation activity of *H. diversicolor* in similar conditions (Bond, 2018). In contrast, *Carcinus maenas*...
did not delay its feeding response to sudden pH drop in presence of conspecific metabolites, which is in line with meta-analyses showing that some aquatic arthropods are more robust to ocean acidification conditions (Kroeker et al., 2013; Wittmann and Pörtner, 2013; Clements and Darrow, 2018). The resilience to pH stress in *C. maenas* may be due to their pH regulatory capacities allowing them to maintain feeding during short-term assays, but they may show altered responses in longer-term assays—for instance after 10 weeks—as their energetic requirements increase (Appelhans et al., 2012; Clements and Darrow, 2018). Alternatively, the fact that *C. maenas* did not respond to pH drop may arise from differences in the type of cues that are presented or that not all behaviours are similarly affected by pH drop (Richardson et al., 2021). Short-term hypercapnia does not seem to be a strong stressor in *C. maenas*, due to its pH-variable intertidal habitat (Fehsenfeld et al., 2011). Other than reduced success ratios, pH drop itself did not induce any avoidance behaviours indicative of stress.

Besides the direct effect of pH drop on behaviour, previous studies on ocean acidification also found contrasting effects of pH drop on predator-prey interactions (Draper and Weissburg, 2019). Here, we observed an increased escaping tendency of *C. maenas* in response to *S. aurata* control metabolites in pH drop but not in control pH. Although this was not the main focus of our study, it could mean that pH drop renders predator odour more potent for its prey, for example through pH-dependent changes in odour molecular structure, receptor binding, or information processing (Munday et al., 2009; Roggatz et al., 2016, 2019; Schirrmacher et al., 2020). Our results contrast with earlier reports of decreased predator avoidance (e.g., in snails; see Jellison et al., 2016; Froehlich and Lord, 2020). Overall, our data suggests that a short-term acute pH drop has the ability to impair decision-making and predator-prey interactions, and in turn alter fitness-relevant behaviours. Nevertheless, future studies should aim to disentangle the effects of pH drop from that of pCO₂, which ideally also would test short, medium, and long-term responses.

### Indirect Effects of pH Drop on Recipients’ Behaviour Through Stress Chemical Communication

Despite the above-mentioned species-specific direct effects of pH drop on behaviour success ratios, we could show here that pH drop also has indirect effects on behaviour by altering chemical communication. We found that stress metabolites released by animals exposed to pH drop altered feeding and burrowing, and increased avoidance behaviours, but that the response was donor and recipient species-specific. Hermit crabs *D. pugilator* did not react to any stress metabolites. Significant responses in the other two recipient species, however, were directionally equivalent to those induced by pH drop itself since it took longer to find a food cue or to burrow the head in the presence of stress metabolites. Although behavioural
stress response propagation through chemical communication is well documented for alarm substances and disturbance cues upon predation stress (Giacomini et al., 2015; Abreu et al., 2016; Mathuru, 2016), our results show here that chemical communication induced by abiotic stressors such as pH drop can trigger the release of waterborne chemicals that in turn trigger a behavioural stress response in its recipients. Stress metabolites conditioned by the potential predator S. aurata induced more avoidance behaviours and delayed feeding in C. maenas and burrowing in H. diversicolor, compared to S. aurata control metabolites. Similarly, the presence of conspecific stress metabolites significantly lowered H. diversicolor burrowing success ratio compared to conspecific control metabolites.

On the other hand, C. maenas did not react to conspecific stress metabolites. The different behavioural effect of conspecific stress metabolites between crabs and H. diversicolor has several possible explanations ranging from different defence strategies related to stress risk perception and evaluation (Hazlett, 1985; Bairos-Novak et al., 2017, 2018; Goldman et al., 2020b) to different types, concentrations, or ratios of the released chemicals that serve as risk cues (Júnior et al., 2010; Morishita and Barreto, 2011). As we have shown here a pH drop to 7.6 is not a strong stressor in crabs (Fehsenfeld et al., 2011) which may explain that we failed to observe responses to water from pH drop-conditioned conspecific green shore crabs. However, the presence of stress metabolites conditioned by S. aurata caused a marked drop in the success ratio of C. maenas at low (but not control) pH, evidenced by significant interaction terms.

Whilst we did not investigate their chemical structure, our experiment allows us to characterise novel properties of stress metabolites. Stress metabolites, like disturbance cues, potentially consist of regularly excreted metabolites such as urea and ammonia (Bairos-Novak et al., 2017, 2018; Goldman et al., 2020b) to different types, concentrations, or ratios of the released chemicals that serve as risk cues (Júnior et al., 2010; Morishita and Barreto, 2011). As we have shown here a pH drop to 7.6 is not a strong stressor in crabs (Fehsenfeld et al., 2011) which may explain that we failed to observe responses to water from pH drop-conditioned conspecific green shore crabs. However, the presence of stress metabolites conditioned by S. aurata caused a marked drop in the success ratio of C. maenas at low (but not control) pH, evidenced by significant interaction terms.

In this study, we could show that short-term pH drop of a similar magnitude of that experienced within the intertidal zone, but also aligned to end-of-century predicted average values (Chavez et al., 2017; Landschützer et al., 2018), had negative consequences on fitness-relevant behaviours in harbour ragworm H. diversicolor and small hermit crab D. pugilator. Additionally, we confirm that pH drop events also impede the same behaviours in the same way indirectly via chemical communication, albeit these effects depended on donor and recipient species. Sea bream S. aurata and harbour ragworm H. diversicolor stressed by pH drop released stress metabolites which possibly differ from control metabolites and negatively affect fitness-relevant behaviours in metabolite recipients. Stress metabolites induced similar avoidance behaviours as those exhibited under physiological stress, meaning that a stress response was propagated from donor to recipient. These negative indirect behavioural effects of pH drop warrant further study, especially as our results were inconclusive with regards to the combined treatments of low pH and stress metabolites. Short-term pH drops thus involve behavioural additionally to metabolic trade-offs, which is also of interest for better predicting the response of natural and aquaculture systems under ocean acidification combined with tidal pH fluctuations. One potential limitation of our experimental design was that we could not achieve individual marking of animals. Despite circulating animals to recovery tanks to limit animal reuse, this may have led to a small degree of animal reuse wherein the full dataset may include animals.
tested at most twice over the course of the experimental period. Nevertheless, we show through random bootstrapping of 50% of the dataset, that the outcomes of the time-to-event analysis remain unchanged even if only half of the observations were analysed, which confirms the validity of our experimental data. Whether or not pseudoreplication is present in ecological studies has been subject to debate (Davies and Gray, 2015), but owing to our large number of observations we can show here that animal reuse had no effect on the model outcomes and effect size was not overestimated. Given the potential high ecological significance of indirect negative effects of pH fluctuations on population fitness, studies aiming to replicate our results should aim to further optimise our experimental design with better technical equipment as that available to us (Baker, 2016).

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

The animal study was reviewed and approved by the University of Hull Ethics Committee under the approvals U020 and FEC_2019_81.

REFERENCES

Abreu, M. S., Giacomini, A. C. V., Gusso, D., Koakoski, G., Oliveira, T. A., Marqueze, A., et al. (2016). Behavioral responses of zebrafish depend on the type of threatening chemical cues. J. Comp. Physiol. A Neuroethol. Sens. Neural Behav. Physiol. 202, 895–901. doi: 10.1007/s00359-016-1129-5

Appelhans, Y. S., Thomsen, J., Pansch, C., Melzner, F., and Wahli, M. (2012). Sour times: seawater acidification effects on growth, feeding behaviour and acid–base status of Asterias rubens and Carcinus maenas. Mar. Ecol. Prog. Ser. 459, 85–98. doi: 10.3354/meps09697

Ashur, M. M., Johnston, N. K., and Dixon, D. L. (2017). Impacts of ocean acidification on sensory function in marine organisms. Integr. Comp. Biol. 57, 63–80. doi: 10.1093/icb/icx010

Bairos-Novak, K. R., Crane, A. L., Achtymichuk, G. H., Hsin, J., Rivera-Hernández, I. A. E., Simko, O. M., et al. (2020). Forget the audience: tadpoles release similar disturbance cues regardless of kinship or familiarity. Behav. Ecol. Sociobiol. 74, 1–10. doi: 10.1007/s00265-020-02936-8

Bairos-Novak, K. R., Crane, A. L., Chivers, D. P., and Ferrari, M. C. O. (2018). Better the devil you know? How familiarity and kinship affect prey responses to disturbance cues. Behav. Ecol. 30, 446–454. doi: 10.1093/beheco/ary184

Bairos-Novak, K. R., Mitchell, M. D., Crane, A. L., Chivers, D. P., and Ferrari, M. C. O. (2017). Trust thy neighbour in times of trouble: background risk alters how tadpoles release and respond to disturbance cues. Proc. Biol. Sci. 284:20171465. doi: 10.1098/rspb.2017.1465

Baker, M. (2016). 1,500 scientists lift the lid on reproducibility. Nature 353, 452–454. doi: 10.1038/s33452a

Bacellos, L. J. G., Volpato, G. L., Barreto, R. E., Coldebellia, L., and Ferreira, D. (2011). Chemical communication of handling stress in fish. Physiol. Behav. 103, 372–375. doi: 10.1016/j.physbeh.2011.03.009

Batten, S. D., and Bamber, R. N. (1996). The effects of acidified seawater on the polychaete Nereis virens Sars, 1835. Mar. Pollut. Bull. 32, 283–287. doi: 10.1016/0025-326X(95)00163-H

AUTHOR CONTRIBUTIONS

KW designed the study. LF, SS, LA, JF, RN, KR, and KW performed the experiments. LF analysed the data and wrote the first manuscript draft with KW, JH, and HB-H. All authors contributed to the final manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2021.773870/full#supplementary-material

Bhuiyan, K. A., Rodriguez, B. M., Pires, A., Ribá, I., Dellvalles, Á, Freitas, R., et al. (2021). Experimental evidence of uncertain future of the keystone ragworm Hediste diversicolor (O.F. Müller, 1776) under climate change conditions. Sci. Total Environ. 750:142031. doi: 10.1016/j.scitotenv.2020.14

Bond, D. (2018). Ocean Acidification Threat? How pH affects Burrowing Behaviour of Neritides Dicorhinalis and Its Bearing on Mass Extinction Scenarios. Munich: EGU.

Briffa, M., de la Haye, K., and Munday, P. L. (2012). High CO2 and marine animal behaviour: potential mechanisms and ecological consequences. Mar. Pollut. Bull. 64, 1519–1528. doi: 10.1016/j.marpolbul.2012.05.032

Burlinson, F. C., and Lawrence, A. J. (2007). Development and validation of a model of oceanic neodymium isotope cycling. Geochim. Cosmochim. Acta 71, 2575–2593. doi: 10.1016/j.gca.2007.01.006

Caldeira, K., and Wickett, M. E. (2003). Oceanography: anthropogenic carbon and ocean pH. Nature 425:365. doi: 10.1038/425365a

Chavez, F. P., Pennington, J. T., Michisaki, R. P., Blum, M., Chavez, G. M., Fiedrich, J., et al. (2017). Climate variability and change: response of a coastal ocean ecosystem. Oceanography 30, 128–145.

Chivers, D. P., Dixon, D. L., White, J. R., McCormick, M. I., and Ferrari, M. C. O. (2013). Degradation of chemical alarm cues and assessment of risk throughout the day. Ecol. Evol. 3, 3925–3934. doi: 10.1002/ece3.760

Clark, T. D., Raby, G. D., Roche, D. G., Binning, S. A., Speers-Roesch, B., Jutfelt, F., et al. (2020a). Ocean acidification does not impair the behaviour of coral reef fishes. Nature 577, 370–374. doi: 10.1038/s41586-019-1903-y

Clark, T. D., Raby, G. D., Roche, D. G., Binning, S. A., Speers-Roesch, B., Jutfelt, F., et al. (2020b). Reply to: methods matter in repeating ocean acidification studies. Nature 586, E25–E27. doi: 10.1038/s41586-020-2804-9

Clements, J. C., and Darrow, E. S. (2018). Eating in an acidifying ocean: a quantitative review of elevated CO2 effects on the feeding rates of calcifying marine invertebrates. Hydrobiologia 820, 1–21. doi: 10.1007/s10750-018-3665-1
Sordo, L., Santos, R., Barrote, I., and Silva, J. (2018). High CO2 decreases the long-term resilience of the free-living coralline alga Phymatolithon lusitanicum. Ecol. Evol. 8, 4781–4792. doi: 10.1002/ece3.4020

Sordo, L., Santos, R., Reis, J., Shulika, A., and Silva, J. (2016). A direct CO2 control system for ocean acidification experiments: testing effects on the coralline red alga Phymatolithon lusitanicum. PeerJ 4:e2503. doi: 10.7717/peerj.2503

Therneau, T. M. (2021). Survival Analysis [R package survival version 3.2-10]. Available Online at: https://CRAN.R-project.org/package=survival (accessed November 2021).

Therneau, T. M., and Grambsch, P. M. (2000). Modeling Survival Data: Extending the Cox Model. Statistics for Biology and Health. Berlin: Springer Science & Business Media. doi: 10.1007/978-1-4775-3294-8

Thomas, J. T., Munday, P. L., and Watson, S.-A. (2020). Toward a Mechanistic Understanding of Marine Invertebrate Behavior at Elevated CO2. Front. Mar. Sci. 7:345. doi: 10.3389/fmars.2020.00345

Toa, D. G., Anfonso, L. O. B., and Iwama, G. K. (2004). Stress response of juvenile rainbow trout (Oncorhynchus mykiss) to chemical cues released from stressed conspecifics. Fish Physiol. Biochem. 30, 103–108. doi: 10.1016/s1030-5392(04)00056-x

Tomsic, D., Sztarker, J., Berón de Astraeda, M., Oliva, D., and Lanza, E. (2017). The predator and prey behaviors of crabs: from ecology to neuronal adaptations. J. Exp. Biol. 220, 2318–2327. doi: 10.1242/jeb.143222

Truchot, J. P., and Duhamel-Jouve, A. (1980). Oxygen and carbon dioxide in the marine intertidal environment: diurnal and tidal changes in rockpools. Respir. Physiol. 39, 241–254. doi: 10.1016/0034-5687(80)90056-0

Velez, Z., Costa, R. A., Wang, W., and Hubbard, P. C. (2021). Independent effects of seawater pH and high P CO2 on olfactory sensitivity in fish: possible role of carbonate anhydride. J. Exp. Biol. 224:ejeb238485. doi: 10.1242/jeb.238485

Wage, J., Rohr, S., Hardege, J. D., and Rotchell, J. M. (2016). Short-term effects of CO2-induced low pH exposure on target gene expression in Platynereis dumerilii. J. Mar. Biol. Oceanogr. 5.2. doi: 10.4172/2324-8661.1000155

Wang, Y., Hu, M., Wu, F., Storch, D., and Pörtner, H.-O. (2018). Elevated pCO2 affects feeding behavior and acute physiological response of the brown crab Cancer pagurus. Front. Physiol. 9:1164. doi: 10.3389/fphys.2018.01164

Watson, G. J., Hamilton, K. M., and Tuffnail, W. E. (2005). Chemical alarm signalling in the polychaete Negotia (Neanthes) virenis (Sars) (Annelida: polychaeta). Anim. Behav. 70, 1125–1132. doi: 10.1016/j.anbehav.2005.03.011

Williamson, P., Pörtner, H.-O., Widdicombe, S., and Gattuso, J.-P. (2021). Ideas and perspectives: when ocean acidification experiments are not the same, repetibility is not tested. Biogeosciences 18, 1787–1792. doi: 10.5194/bg-18-1787-2021

Wittmann, A. C., and Pörtner, H.-O. (2013). Sensitivities of extant animal taxa to ocean acidification. Nat. Clim. Chang. 3, 995–1001. doi: 10.1038/nclimate1982

Wolf, K., Nguyen, H. D., Davey, M., and Byrne, M. (2020). Characterizing biogeochemical fluctuations in a world of extremes: a simulation for temperate intertidal habitats in the face of global change. Glob. Chang. Biol. 26, 3858–3879. doi: 10.1111/gcb.15103

Wu, F., Wang, T., Cui, S., Xie, Z., Dupont, S., Zeng, J., et al. (2017). Effects of seawater pH and temperature on foraging behavior of the Japanese stone crab Charybdis japonica. Mar. Pollut. Bull. 120, 99–108. doi: 10.1016/j.marpolbul.2017.04.053

Wyatt, T. D., Hardege, J. D., and Terschak, J. (2014). Ocean acidification foils chemical signals. Science 346:176. doi: 10.1126/science.346.6206.176-a

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