

## Research



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# Meta-analytic evidence for quantitative honesty in aposematic signals

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The combined use of noxious chemical defences and conspicuous warning colours is a ubiquitous anti-predator strategy. That such signals advertise the presence of defences is inherent to their function, but their predicted potential for quantitative honesty—the positive scaling of signal salience with the strength of protection—is the subject of enduring debate. Here, we systematically synthesized the available evidence to test this prediction using meta-analysis. We found evidence for a positive correlation between warning colour expression and the extent of chemical defences across taxa. Notably, this relationship held at all scales; among individuals, populations and species, though substantial between-study heterogeneity remains unexplained. Consideration of the design of signals revealed that all visual features, from colour to contrast, were equally informative of the extent of prey defence. Our results affirm a central prediction of honesty-based models of signal function and narrow the scope of possible mechanisms shaping the evolution of aposematism. They suggest diverse pathways to the encoding and exchange of information, while highlighting the need for deeper knowledge of the ecology of chemical defences to enrich our understanding of this widespread anti-predator adaptation.

## 1. Introduction

Predation has driven the evolution of striking adaptations for defence among prey [1–3]. Few strategies are as widespread as aposematism which, in its best-studied form, is characterized by the coupling of chemical defences with conspicuous colour patterns as aversive ‘warnings’ to predators [4]. That such colours are qualitatively honest in signalling the presence of defences is an inherent feature of aposematism, and their evolutionary stability is a predictable consequence of the broad alignment of interests between signallers and receivers [5,6]. In general terms, predators avoid the costs of a noxious meal while prey reduce the risk of injury or death, and the system is resistant to cheating since weakly defended prey are less able to bear the costs of predation [7,8]. While the qualitative honesty of aposematic signals is well established, their potential for quantitative honesty—defined by a positive, linear correlation between colour signal expression and the quality of defences—is less clear.

The question of quantitative honesty in aposematism has received extensive theoretical attention (table 1). The earliest support arose from the consideration of aposematic signals as handicaps (*sensu* [16]), which suggested that positive correlations may emerge assuming either a (unspecified) mechanistic link between chemical defences and signal expression, or more general predation costs which are differentially borne across signallers [17]. While those strictly Zahavian explanations have been criticized for biological implausibility [7], later models both tangential to and outside of the framework identified plausible routes to quantitative honesty (e.g. [9,11,12,18]). Blount *et al.* [9] presented arguments for energy, or energy turnover, as a shared and limited resource in the synthesis of both chemical defences and pigments. This was extended by

**Table 1.** Summary of the predicted associations between the expression of aposematic signals and quality of chemical defences. Scales and signs refer to the level at which quantitative associations may manifest and the direction (+ or −) or absence (none) of any linear correlation, respectively, with ‘quantitative honesty’ represented by positive correlations at each scale. References detail theoretical treatments supporting the noted mechanisms, and asterisks (\*) indicate scales at which the plausibility of a mechanism was extrapolated (in the original study) rather than explicitly examined.

scale	sign	mechanism(s)	references
among individuals	+	go-slow prey sampling; handicap via resource trade-off; automimicry; exaptation	Blount <i>et al.</i> [9], Guilford [10]; Speed & Franks [11]; Holen & Svanungsen [12]; Lee <i>et al.</i> [13]
	−	high innate defence efficacy; non-limiting resources	Blount <i>et al.</i> [9]; Lee <i>et al.</i> [13]
among populations	+	go-slow prey sampling*; handicap via resource trade-off*; Batesian mimicry; correlated marginal costs; automimicry	Blount <i>et al.</i> [9]; Franks <i>et al.</i> [14], Guilford [10], Speed & Ruxton [15]; Speed & Franks [11]; Holen & Svanungsen [12]
	−	fecundity-linked display costs; non-limiting resources*	Blount <i>et al.</i> [9]; Speed & Ruxton [15]
among species	+	go-slow prey sampling*; handicap via resource trade-off*; Batesian mimicry; correlated marginal costs; automimicry*	Blount <i>et al.</i> [9]; Franks <i>et al.</i> [14], Guilford [10], Speed & Ruxton [15]; Speed & Franks [11]; Holen & Svanungsen [12]
	−	fecundity-linked display costs; non-limiting resources*	Blount <i>et al.</i> [9]; Speed & Ruxton [15]
none	none	low or variable marginal costs; no shared signal/defence resources	Guilford & Dawkins [7]; Speed & Ruxton [15]

Holen & Svanungsen [12] as part of a broader set of evolutionarily stable strategy models, and affirmed the view that effective honesty may arise among individuals when resources are shared between the synthesis of defences and signals and, hence, trade-off during allocation. Plasticity [11], Batesian mimicry [14,19] and predator cognition [12] have been variously examined in alternative models, with several apparent routes to stable positive correlations between the level of defence and signal expression now identified (reviewed in [20]).

Despite mechanistic differences, the potential for quantitative honesty has found broad theoretical support (albeit not universal; table 1), and empirical efforts have chiefly focused on testing the existence and direction of predicted correlations. The results have been equivocal. Positive correlations, and hence quantitative honesty, are apparent among several species of coccinellid beetle, in which the levels of endogenously synthesized alkaloids—precoccinelline and/or coccinelline—covary with the conspicuousness of their bold, spotted signals [9,21,22]. By contrast, in the long-studied poison dart frogs, only negative correlations were identified between the potency of alkaloids and signal salience across species of *Ameroegea* [23] and across populations of *Oophaga* [24]. An earlier study found no relationship at all [25], however, while more recent work in the group found moderate to strong positive correlations on the whole [26–28]. Analogous tests in wasps [29], moths [30], salamanders [31] and sea slugs [32] add to the accumulating evidence, though the central shared prediction of honesty-based models remains unresolved.

Inherent to the question of the existence of quantitative honesty is the scale at which signal/defence correlations should manifest. As above, much of the focus has been on the origins and maintenance of among-individual correlations, though similar potential exists at the scale of populations and even species [11,15,33]. Positive correlations among populations may arise, for example, if the production

costs of signals and defences scale in unison, or if the density of prey and the risk of predation vary across space [15,34]. If Batesian mimicry is at play then antagonistic coevolution may select for increasing conspicuousness among model animals across species or populations, to a similar end [14]. Holen & Svanungsen [12] too, although focused on among-individual honesty, note that the stable equilibria arising from ‘go-slow’ [10] and resource allocation trade-off [9] mechanisms likely extend to the scale of populations and species. By contrast, Leimar *et al.*'s [33] game-theoretical treatment showed that negative among-population correlations are possible when the strength of defences vary. Wider-ranging optimization models reveal similar flexibility in potential sign of cross-species correlations, with negative associations arising when marginal costs of defences or displays vary [15]. In empirical terms, this question has also received mixed support. Positive correlations across species [22,26,27] are met with negative counter-examples [23], while among populations each of positive [28], negative [24] and the absence of correlations [25] have been documented.

This expanse of empirical work on aposematic honesty is invaluable, but diversity in signal designs, chemical defences and the measurement of each is challenging for qualitative synthesis. Modern quantitative methods, however, provide robust tools for capitalizing on such variation, and so can offer substantive insight into longstanding questions [35,36]. To that end, we conducted a meta-analysis to examine whether and to what extent aposematic signals encode quantitatively honest information on chemical defences in prey. Specifically, we synthesized estimates of the correlation between the visual features of aposematic signals and chemical defences to test the presence and sign of the predicted covariation at three scales: among individuals, populations and species. The central shared prediction of honesty-based models is a positive correlation between the expression of signals and quality of chemical defences, with a negative or non-

existent relationship favouring an alternate set of candidate mechanisms governing the coevolution of aposematic signals and defences (table 1).

## 2. Methods

### (a) Literature search and study selection

We conducted a systematic search of the scientific literature using the *Web of Science* and *Scopus* databases for publications up to July 2020. Following initial scoping searches, we used the search string ((aposemati\* OR warning colo\* OR warning signal) AND (honest\* OR toxic\* OR chem\* OR handicap OR quantitative OR unpalatab\* OR unprofit\*)). In the *Web of Science* database, we also refined by the categories ecology, evolutionary biology, environmental sciences, zoology, biology and behavioural sciences. Our search returned 735 studies following the removal of duplicates, of which 24 were ultimately appropriate for quantitative synthesis, including three studies identified through references list searches (see electronic supplementary material, figure S1 for PRISMA diagram, and electronic supplementary material for further search details).

We included all publicly available studies (peer-reviewed, preprint or theses) that empirically examined the scaling relationship between a continuous measure of the quality, efficacy and/or quantity of chemical defences (internal or secreted), and aposematic signal appearance in organisms, or which contained sufficient data for such relationships to be estimated directly (electronic supplementary material, table S1). Included studies could be experimental or observational and could test the relationship at any scale: among individuals, populations or species. Among individuals, such correlations were typically estimated from individual-level measures of signal appearance and chemical defence (further detailed below) across a sample of prey organisms from a single population. This general procedure is true of studies at higher scales too, albeit with population- or species-level averages of signal appearance and chemical defence underlying the estimated correlation(s). We excluded commentaries and reviews, effects collected from known Batesian mimics, or measures derived from artificial prey. We contacted authors to request necessary data where it was not available ( $n = 1$ ) and excluded these studies if it could not be obtained.

### (b) Data extraction and effect size calculation

We used the correlation coefficient Pearson's  $r$ , transformed to Fisher's  $z$  (for its normalizing and variance-stabilizing qualities), as the effect size describing the relationship between aposematic signal coloration and prey defences for meta-analysis. These effects were extracted directly from the study text, converted from available test statistics or estimated from digitized figures using the R package 'metaDigitise' v.1.0 [37].

We also recorded information from each study, both theoretical and methodological, which we *a priori* hypothesized may moderate the strength of any relationship between colour and defences. This included the scale at which signal/defence correlations were estimated; among individuals, populations or species. We also examined the method used for quantifying chemical defences, since standard approaches fall into two categories. The first includes those studies that directly measure the concentration, quantity or diversity of specific compounds which invoke aversive responses in predators, such as alkaloids (e.g. [21,38,39]). The second general approach is to use bioassays in which proxy organisms are exposed to the relevant compounds or tissues containing them, such as skin extracts. Examples include exposing *Daphnia* to presumed toxins and recording mortality [22,40] or injecting mice with tissue extracts and recording irritation and/or mortality [23,28]. We, therefore,

coded each study dichotomously depending on which of the two general methods was used. Where necessary we also adjusted the directionality of measures so that they represented the same relationship (e.g. by converting *Daphnia* survival to mortality).

Rich methods are also available for quantifying the expression of colour signals, which vary in their intent [41,42]. Some centre on estimating the properties that describe absolute colour appearance; hue (the unique colour), saturation (spectral richness or purity), brightness (or 'lightness,' in human terms) and size (relative or absolute). While others attempt to capture the contextual conspicuousness of signals through measures of contrast. This may entail using visual models to first estimate the viewer-subjective appearance of colours, before measuring the difference between colours within a colour pattern (*internal* contrast), or the overall difference between colour patterns and natural viewing backgrounds (*external* contrast). In all cases, theory predicts positive covariation between signal measures and defence levels as a signature of quantitative 'honesty'. The one exception is signal 'hue', which is a directionless measure. That is, predictions of its scaling relationship with defences require mechanistic insight into colour and defence production, and knowledge of the environments in which it is viewed. We, therefore, took the absolute value of correlations between signal hue and defences throughout. A sensitivity analysis showed the only qualitative effect of this decision lay in the statistical significance of hue itself, which falls slightly below the threshold when considered on its original scale ( $r = 0.208$ , 95% CI =  $-0.04$ ,  $0.43$ ). Beyond signal hue, we coded all effects as quantifying one of saturation, brightness, size, internal contrast or external contrast.

### (c) Meta-analyses

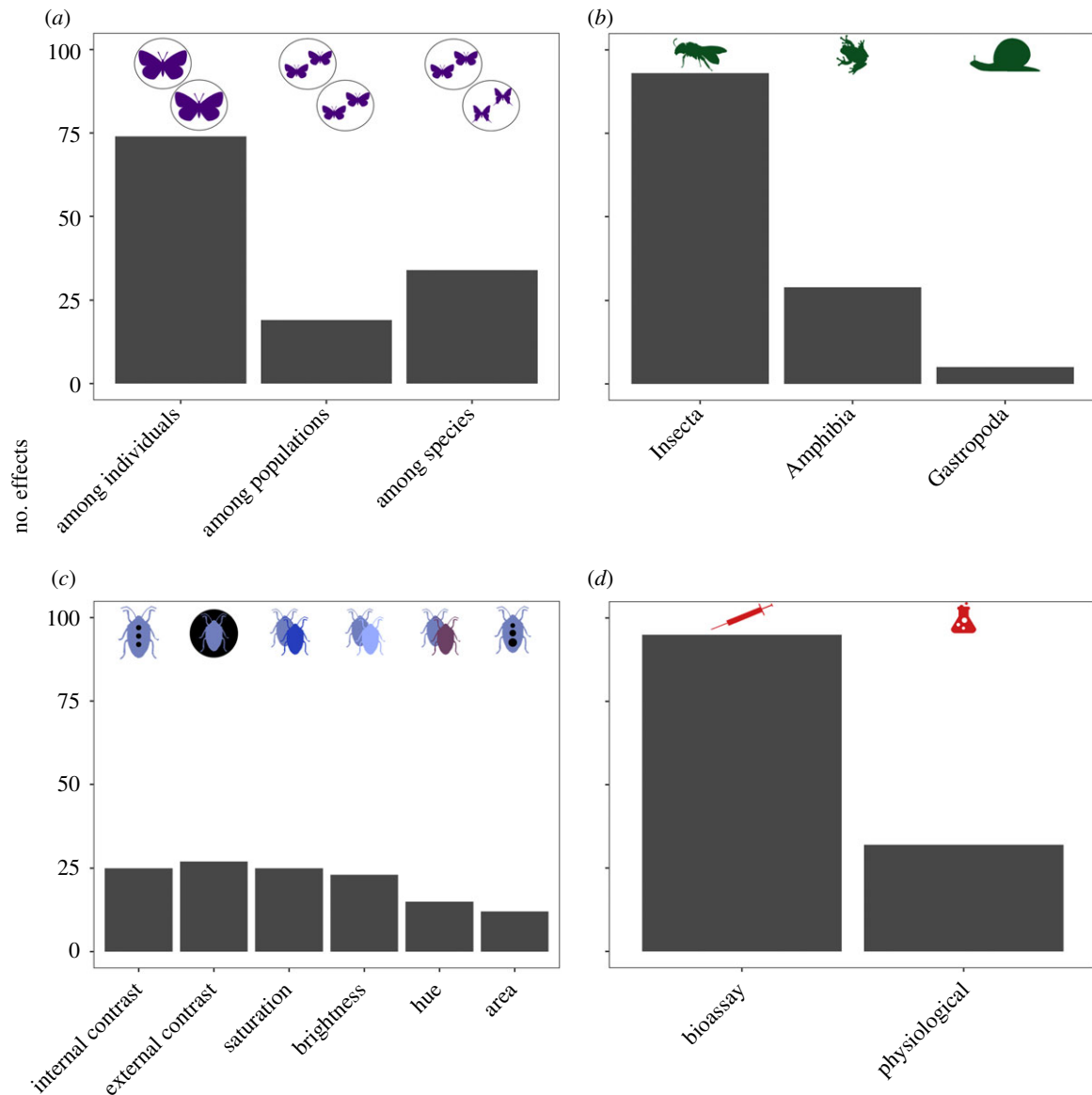
We ran both multi-level meta-analytic (intercept-only, MLM) and multi-level meta-regression (MLMR) models, using the package *metafor* v.2.1.0 [43] in R v.4.0.1 [44]. Almost all studies reported multiple effects so we included a study-level random effect in all models (following validation, see electronic supplementary material), as well as an observation-level effect to estimate residual variances which *metafor* does not report by default. Furthermore, multiple distinct measures—such as the hue, saturation and brightness of signals—are often collected from a single individual or group, and so are likely to be more correlated than those collected from independent groups. These correlations are almost never reported in original studies, and regularly go unconsidered in the meta-analysis, so we conservatively accounted for this possibility by fitting the off-diagonal covariances in the sampling covariance matrix assuming a correlation of  $r = 0.5$ . In all models, we consider effect size estimates whose 95% confidence intervals do not overlap zero to be statistically significant.

### (d) Publication bias

We formally tested for evidence of publication bias by visually inspecting a funnel plot of effect sizes versus standard errors for symmetry, and through an Egger's test on an intercept-only MLMA that included the full random effects structure described above [45].

## 3. Results

Our final analysis included 127 effect sizes from 24 studies [21–23,26–32,38–40,46–56]. Most studies reported multiple effects, with a mean of 6 and range of 1–27. Some 22 species were represented in total (considering only species-level studies), spanning three classes: insects, gastropods and amphibians (figure 1). With respect to the scale of the



**Figure 1.** The number of included effects by (a) scale, (b) taxa, (c) aspect of aposematic signal design and (d) measure of chemical defence. (Online version in colour.)

study, 74 effects (from seven studies) estimated signal/defence correlations among individuals, 19 (via four studies) were measures among populations and 34 (from 15 studies) were among species.

Across all studies, we identified a moderate positive correlation between aposematic colour signal expression and chemical defences (meta-analytic mean  $Z = 0.34$ , 95% CI = 0.19–0.47), as consistent with a prediction of quantitative honesty (figure 2). Effect size heterogeneity was moderate to high ( $I^2 = 0.70$ , 95% CI = 0.59–0.79) which is typical in ecology and evolutionary biology and suggests that variation among studies is not explicable by sampling variance alone. Notably, the positive correlation between signals and defences held across scales (table 2 for numerical results henceforth). That is, the correlation was moderate and positive irrespective of the scale at which the relationship was examined—among individuals, populations or species—though it is weakest, and our estimate least-precise, at the among-population scale in light of the relatively smaller sample size. All components of warning signals were similarly informative of prey defences, with each of signal hue, saturation, brightness and area, as well as internal and external contrast, scaling positively with the level of chemical defence.

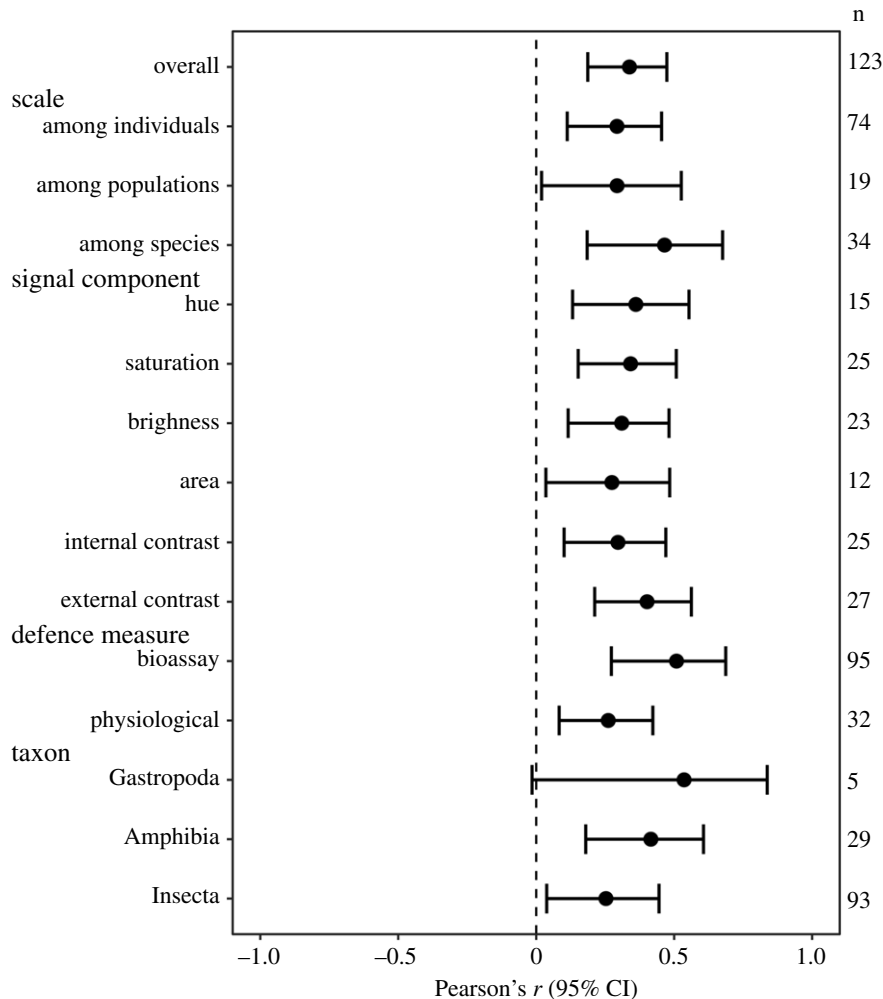
These relationships also held irrespective of the way in which defences were quantified. Effects estimated from bioassay-based methods tended to be stronger than those using physiological measures of chemical quantity or diversity, but only slightly so. Finally, signal–defence correlations were similar in direction and magnitude among amphibians and insects though not gastropods (for whom the confidence interval included zero), which is unsurprising given the small sample of available effects for that group.

#### (a) Publication bias

Visual inspection of the funnel plot suggested no identifiable asymmetry and hence no evidence of publication bias (electronic supplementary material, figure S2), which was supported by an Egger's test (estimate 95% CI =  $-0.25$ – $0.07$ ,  $t_{125} = -0.03$ ,  $p = 0.98$ ).

## 4. Discussion

Conspicuous warning colours are known to advertise the presence of defences among prey [57,58]. The question of *quantitative* honesty—the positive scaling of signal expression



**Figure 2.** Forest plot denoting the meta-analytic mean effect, and moderators of the correlation between aposematic signal expression and chemical defences in prey. Shown are Pearson's correlations backtransformed from Fisher's  $z$ , with 95% confidence intervals about the mean. Sample sizes are displayed on the right. 'Scale' indicates the level at which correlations were estimated, while 'signal component' captures the aspect of aposematic signal appearance against which the level of defence was correlated. 'Defence measure' differentiates effects estimated via the use of bioassays versus direct measures of the quantity and/or diversity of defensive chemicals.

and defences—has remained contentious, however, with contrasting theoretical (table 1) and equivocal empirical [28,40,52] support to date. Here, we report meta-analytic evidence for a positive correlation between aposematic signal structure and prey defences, as consistent with a prediction of quantitative honesty. Notably, this correlation holds at all scales; among individuals, populations and species, though significant between-study heterogeneity remains unexplained. Both absolute signal features, such as saturation and brightness, and contextual measures of conspicuousness, were salient channels of information on the extent of defences, and the relationship held irrespective of the measure of chemical defence used.

These results contradict early theory [33] and support the central shared prediction of a positive signal–defence correlation among honesty-based models [9,12]. The strength and consistency of effects across scales (figure 2) argues for generality in the underlying mechanism, for which resource allocation trade-offs and 'go-slow' prey sampling are promising candidates (table 1; [9,12]). The former predicts the emergence of positive correlations across scales given a key assumption—competition for resources within individuals—is met [9,12]. The exact form this competition takes remains unknown, though antioxidant-mediated trade-offs

have been proposed [9], in an argument which echoes similar work on pigment-based sexual signals [59,60]. Coccinellid beetles present a promising example, among whom the maternal allocation of both pigments and precoccinelline may underlie adult signal honesty through the metabolic conversion of the latter *in ovo* [38,47]. Resource-dependent variation in signal/defence correlations [38] and the negative scaling of predation rates with conspicuousness [22] strengthen the case and offer the firmest line of evidence for resource mediated trade-offs as a driver of signal honesty, as broadly consistent with our results.

The 'go-slow' sampling of prey, by contrast, emphasizes predator cognition as a driving force in the evolution of aposematism. The central insight is that if conspicuous prey tend to be better defended, and predators are able to discriminate among prey based on the basis of chemical defences and colour, then predators should be more wary when sampling conspicuous prey [10,12]. The process of taste-rejection will thus lead to differential prey survival as a function of conspicuousness. And if the costs of increased conspicuousness are unequally borne across well- and poorly defended prey, then positive signal/defence correlations will result [10–12,18]. Dedicated tests of the hypothesis do not yet exist, though key underlying

**Table 2.** Full parameter estimates from MLM and MLMR models of the mediators of the correlation between aposematic colour signal expression and chemical defences. Shown are sample sizes, mean Pearson's  $r$  (backtransformed from Fisher's  $z$ ), lower and upper 95% confidence intervals and heterogeneity ( $I^2$ ).

	$r$	lower CI	upper CI	$n$	$I^2$
overall					0.70
intercept-only	0.34	0.19	0.47	123	
scale					0.70
among individuals	0.29	0.11	0.45	74	
among populations	0.29	0.02	0.53	19	
among species	0.47	0.18	0.68	34	
signal component					0.70
hue	0.36	0.13	0.55	15	
saturation	0.34	0.15	0.51	25	
brightness	0.31	0.12	0.48	23	
area	0.27	0.04	0.48	12	
internal contrast	0.30	0.10	0.47	25	
external contrast	0.40	0.21	0.56	27	
defence measure					0.69
bioassay	0.51	0.27	0.69	95	
physiological	0.26	0.08	0.42	32	
taxon					0.70
Amphibia	0.42	0.18	0.61	29	
Gastropoda	0.54	-0.02	0.84	5	
Insecta	0.25	0.04	0.45	93	

assumptions have found in-principle support. Common terrestrial [61–64] and marine [65] generalist predators are capable of taste-rejecting prey on the basis of their chemical defences, as well as discriminating among the visual features of signals [66–68]. Conspicuousness and defences have also been shown to interact to increase the probability of prey rejection [69,70], in part through a learned wariness toward conspicuous prey [71]. The taxonomic and ecological breadth of this work suggests ‘go-slow’ sampling as an appealing catch-all explanation, in keeping with the generality of our findings (table 2). Nonetheless, the empirical case for predator cognition driving quantitative honesty is underdeveloped and is an exciting area for attention.

A striking feature of extant work is that all visual properties of aposematic signals, both contextual (e.g. contrast) and absolute (e.g. hue, saturation), are, on average, reliable channels of information on prey defences. This is reflective of the diverse demands on signal efficacy, which include the need for salience within noisy viewing environments, and the government of cognitive processes such as generalization, categorization and memorization in viewers [72–75]. The former is defined by conspicuousness, both internal and external pattern contrast, which relates the structure of signals to their detectability amidst the desaturated hues of natural vistas [22,28,76,77]. The reliable memorization and categorization of stimuli, by contrast, is tied to the features of colour, brightness (albeit less often) and their spatial arrangement [76,78,79]. This functional partitioning of contextual and absolute signal features is similarly borne out in combined tests. Birds, for example, can learn to remember and discriminate among prey on the basis of colour, but

are consistently drawn to greater contrast irrespective of prior experience [74,80].

It is clear, then, that no signal feature is singularly informative of prey defences to predators. Note too, however, that this may partly be due to correlations among signal elements which are inherent to colour production. The chromaticity and brightness of patches tend to covary with contextual measures of external conspicuousness, since natural scenes are often dominated by the dull browns, greys and greens of earth and foliage [81]. Correlations exist among absolute features too, owing to the physics of light absorption by pigments and scattering by nano-structures [82]. The strength of these effects is likely limited, however, as suggested by the aforementioned evidence of selection on and attention to distinct signal components by viewers. Prey behaviour also works to degrade these links, as individuals actively modify their contextual conspicuousness independently of the ‘fixed’ visual features of their signals (e.g. [83,84]). More generally, our finding that all aspects of aposematic signals may reliably inform viewers of prey defences suggests there are myriad routes to effective advertisement. When considered alongside the stability of correlations at the scale of populations and species (which span a breadth of signal designs), these results also touch on the standing question of why aposematic signals are often variable. That is, there appears to be few fundamental design constraints on signals, at least with respect to their potential for honesty (figure 2), which is consistent with the emerging appreciation of diversity in aposematic signals as the norm, rather than a ‘paradox’ [85].

One note of caution is warranted when interpreting the strength of effects in biological, rather than statistical, terms. The visual appearance of signals and efficacy of chemical defences, and hence the honesty of advertisements, are ultimately subjective. Measures of each must, therefore, be calibrated against the perceptual experience of ecologically relevant receivers. With respect to signals, this is increasingly possible through the use of methods for capturing subjective visual experiences (reviewed in [41,86,87]) which continue to be applied and tested in the context of aposematism [22,53,67,78]. Progress in understanding the ecology of chemical defences as they relate to prey sampling and survival has been more gradual (though unabating, e.g. [88–90]), and some fundamental questions remain. The extent to which *Daphnia* spp. mortality or time-to-recovery in mice—common measures of prey ‘toxicity’—map to the responses of predators and, consequently, prey fitness, is untested. Similarly, our ability to infer predator perception and prey survival from the measured concentration of defensive chemicals is limited by the sheer complexity of the physiological and ecological pathways linking these processes (reviewed in [91]). Continued developments in these fields will be immensely valuable, then, not least for further grounding the signal–defence correlations here identified (figure 2) in ecological and evolutionary reality.

Aposematism is an exemplar of anti-predator defence, and its study has driven general advances in evolutionary ecology [1]. That warning signals appear quantitatively honest resolves a key problem in our understanding of their

function and evolution, though much remains to be learned. Knowledge of the physiological and/or ecological processes linking signal expression to defences is paramount, for which work on signal honesty, condition-dependence and oxidative stress in sexual systems may prove informative [92–95]. With respect to signal design, the targets of selection are only understood in general terms [96]. The relative contributions of chromatic (colour) and achromatic (brightness) conspicuousness to signal salience is unresolved [76,80], for example, as is the importance of within-pattern versus against-background contrast for viewer detection and cognition [67,80]. These are exciting areas for progress on a captivating feature of the natural world.

**Data accessibility.** All data and code underlying our analyses are available on GitHub ([https://github.com/EaSElab-18/ms\\_metawarn](https://github.com/EaSElab-18/ms_metawarn)) and have been persistently archived via Zenodo [97].

**Authors' contributions.** T.E.W.: conceptualization, data curation, formal analysis, methodology, project administration, visualization, writing original draft, review and editing; K.D.L.U.: conceptualization, formal analysis, methodology, writing original draft, review and editing. All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

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