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Original Article

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Perceptions about the use of behavioral (eco)toxicology to protect human health and the environment

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Abstract

The One Health concept strongly brings into focus the important connections for human and ecosystem health. However, the incorporation of behavior method guidelines in risk assessment and regulation/policy is not equal between human and ecological disciplines. A survey was conducted on the perceptions and role of behavioral (eco)toxicology in the protection of human and ecosystem health. Those surveyed include scientists working in the field of environmental toxicology and behavioral ecology, representing industry, government, nongovernment organizations, and academia/research centers. The respondents ($N = 166$) agreed that contaminants "can impact" and "are impacting" wildlife (97% and 77%) and humans (84% and 62%, respectively). Overall respondents believed behavioral experiments to be repeatable (60%), reliable (61%), and relevant (84%), although those not studying behavior (43%) were more cautious in their answers. Respondents were more likely to be neutral when asked whether behavioral endpoints are more sensitive (43%), but they agreed (80%) that behavioral endpoints provide important alternative information to standard endpoints. The largest group disagreed (42%) with the statement that behavioral endpoints are currently used in risk assessment but agreed that they were essential (55%). The majority of respondents disagreed (63%) that we understood the risks of contaminants to human and ecosystem health, but they agreed (68%) that regulatory authorities should consider behavioral endpoints. When answers were compared among sectors (academia, government, or industry), industry scientists were more likely to be negative or neutral in their responses to the application of behavioral toxicology. We discuss how these data could be used to support our understanding of and confidence in the effects of contaminants on human and ecosystem health.

Keywords: behavioral toxicology, regulation, risk assessment, industry, conflicts of interest

Introduction

Over the past decade, there has been a considerable renaissance in the field of behavioral ecotoxicology driven by technological advances and the need to understand the sublethal environmental impacts of contaminants, including those of emerging concern, such as neurologically active pharmaceuticals (Ågerstrand et al., 2020; Bertram et al., 2022; Ford et al., 2021; Martin et al., 2025). For example, Bertram et al. (2025) reported a 34-fold increase in the number of articles reporting behavioral endpoints in ecotoxicology between 2000 and 2023. Despite this increase, the use of ecotoxicity studies investigating behavioral endpoints in chemical regulation remains low, even though, at least in the European Union, there are no apparent legal obstacles for endpoints deemed relevant at the population level (Ågerstrand et al., 2020). The One Health concept strongly brings into focus the important connections for human and ecosystem health (Evans and Leighton, 2014). However, currently there is very little connectively between human toxicology and ecotoxicology with respect to behavioral (eco)toxicology. Ford et al. (2021) highlighted a growing concern that ecotoxicology data used in regulatory programs do not adequately consider behavior, primarily due to a lack of standardized toxicity methods (e.g., from the Organisation for Economic Co-operation and Development [OECD]). To improve understanding of the challenges and opportunities for behavioral ecotoxicology, a set of consensus perspectives and recommendations was formed that promise to serve as a road map for advancing the interface between basic and translational science and regulatory practice (Ford et al., 2021). During this process, it became apparent that there are varied opinions and perceptions regarding the potential regulatory use of behavioral toxicology data, which may form an impediment to moving the field forward in a regulatory capacity.

Interestingly, some chemical contaminants are regulated for their known effects on behavior in humans, including restrictions of alcohol consumption and certain drugs while driving or operating machinery (Eisenberg, 2003; Hingson et al., 1988). The U.S.

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Centers for Disease Control and Prevention (2025) now provides public health guidance on driving and cannabis use. While cannabis is legal in some U.S. states, law enforcement officers can pull someone over to conduct a sobriety (behavior) test if they suspect that the person is operating a car, boat, or other vehicle under the influence of cannabis (California State Government, 2025). This highlights how policies have quickly changed to regulate behavioral changes associated with chemical exposure. Other regulated measures to safeguard human health have been enforced due to the well-known effects of metal contamination on neurodevelopment and cognitive function in children (Counter & Buchanan, 2004; Davidson et al., 2004; Lidsky & Schneider, 2003; Lopuszanska & Samardakiewicz, 2020; Sanders et al., 2009). There is also a growing body of research linking air pollution to neurological disorders such as Parkinson's, Alzheimer's, and Huntington's disease (Costa et al., 2020; Kilian & Kitazawa, 2018; Murata et al., 2022). It is known that the pharmaceutical industry invests considerable resources into drug development using behavioral endpoints in animal models for antidepressants and antianxiety drugs (Dash & Patnaik, 2023; de Abreu et al., 2021), as well as screening drugs for their potential to be addictive to patients. The existence of these international regulatory frameworks for health and safety and building compliance (e.g., removal of lead pipes), plus the widespread use of behavioral endpoints in the pharmaceutical industry, suggests at least partial acceptance of their utility and acceptance by the private sector (Ford et al., 2021).

The field of psychology and sociology has been in somewhat of a crisis following considerable attention paid to the reproducibility of studies, many of which span the behavioral sciences (Baker, 2016; Bryan et al., 2021; Laraway et al., 2019). Similar concerns have been raised in behavioral ecotoxicology following the expansion of studies primarily examining the potential impact of pharmaceuticals (e.g., antidepressants and antianxiety medications), often involving new model species, endpoints, and experimental designs (Tanoue et al., 2019). Behavioral experiments have been used in environmental toxicology since the 1970s, when data were obtained in real time or from recorded observations by humans, leaving the potential for observer bias (Ford et al., 2021). While various technologies and automated tracking software have improved the accuracy and diversity of data obtained by removing human observers from the equation, there have still been concerns over the high variability of behavioral data (Ford et al., 2021; Pyle & Ford, 2017). This high variability has in turn led to the need for careful attention to experimental design and statistical approaches (Melvin et al., 2017). In particular, it can be difficult to distinguish between "what is noise" and "what is real information" when assessing intraspecies variability, the temporal nature of some behaviors, or personality traits in wildlife.

Therefore, the aim of this study was to seek the experience and opinions of those working in the fields of environmental toxicology and/or behavioral ecology to inform how different sectors perceive the reliability and relevance of behavioral studies and whether and how behavioral data could be used for real-world benefits for human and ecosystem health.

Materials and methods

Between July and November 2023, members of seven toxicological and 11 behavioral/zoological societies were invited via email or society interest groups to complete a survey addressing the use of behavioral (eco)toxicology to protect human health and the environment (see online supplementary material Table S1). This study was reviewed and approved by the Science and Health Faculty Ethics Committee at the University of Portsmouth (SHFEC 2023-052). The survey was divided into two sections. The first section contained information on the respondents: age, profession, societal affiliations, nationality, country of work, whether they worked with behavioral endpoints, which model species they worked with, and whether they worked primarily in the field or the laboratory. In the context of this article, we refer to toxicology as the discipline and to environmental toxicology, ecotoxicology, and human toxicology as subdisciplines. We refer to environmental toxicology as encompassing the study of environmental contaminants on human health and the environment, although we recognize that other common definitions more narrowly focus on human health implications of environmental exposure—that is, environmental toxicology—and we consider human toxicology as the study of human health only. When referring to ecotoxicology and human toxicology, we use the term *(eco)toxicology*. The second section of the survey focused on the respondents' perceptions of the impact of behavior-altering contaminants on humans and wildlife, the reliability and reproducibility of behavioral (eco)toxicology research, and the importance of behavioral (eco)toxicology in risk assessment and regulation. The respondents were given options to strongly agree, agree, disagree, strongly disagree, neither agree nor disagree (be neutral), or answer "don't know." The proportions of groups that answered different categories were analyzed by Fisher's exact test. Where significant differences arose among academia, government, and industry, sectors were serially remove to assess which were driving the difference in opinion.

Respondents were allowed to expand their responses as free-text comments. All free-text comments were qualitatively analyzed for insights into the perceptions of the respondents from different sectors. Qualitative research aims to get a better understanding of a phenomenon through the experiences of those who are directly involved. An important feature of this approach is that it can provide empirical research with a deeper and more nuanced understanding of respondents' opinions and actions (Castleberry & Nolen, 2018). In the context of the current study, this would translate into perceptions of the reliability and relevance of behavioral studies by those working in the fields of environmental toxicology and behavioral ecology and their perceptions of how behavioral data could be used to inform human health and environmental protection, if at all. The free-text comments were analyzed through qualitative thematic text analysis (Kuckartz, 2019). First, the comments were grouped by sector. The sectors with fewer than four text comments per statement were deemed too scarce to make any collected predictions and were therefore excluded. This left three sectors: academia, government, and industry (which includes consultancy). Furthermore, the data were disassembled to identify patterns concerning the opinions on the survey topics among the sectors in which responses were received. The responses were compiled into a document and color-coded according to similarities and differences in relation to the main statements and in accordance with the protocol for qualitative thematic text analysis. Tendencies that could be deemed typical and/or relevant for a group were determined and reassembled into themes. The themes were adjusted to fit the aims of the study and the statements in the survey. General perceptions and nuances were accounted for and highlighted in quotations. This way of presenting the results adds to the transparency of the analytical process as it shows how the empirical material was used to generate themes and come to conclusions. As the comments were in the form of free-text answers up to five statements and/or questions at a time, the answers could vary substantially to the aspect of the grouped statements that their comments were addressing. This led to some topics gaining more attention from the respondents while others received few or no written comments. Consequently, some comments could not be used in the empirical analysis as some survey parts were left unanswered by respondents or there were too few comments to analyze (fewer than four text comments per section). Finally, although not generalizable without additional research, the findings can provide insight on the process of analytic generalization as they can be applied to the study area of how different sectors believe behavioral data could project human and ecosystem health.

Results

Respondent profiles

In total, we obtained 166 responses from scientists representing 27 countries and 28 nationalities. The United States was the most represented country with 51% of the respondents, followed by Germany (14%), Canada (8%), the United Kingdom (6.6%), and France (4%). The age demographic of respondents was 4% for 18 to 24 years, 29% for 25 to 39, 53% for 40 to 59, and 14% for ≥60. No information on sex and/or gender was recorded. Overall 57% of the respondents had previously worked with behavioral endpoints in (eco)toxicology and/or ecology; 47% worked in academia, 21% in government and/or government agencies and research laboratories, and 27% in industry/consultancy. The remaining respondents (~5%) worked in environmental nongovernment organizations or research laboratories with unknown governance or were retired. Respondents from academia had the greatest proportion working with behavioral endpoints in their research (67%) as compared with government (48%) and the industry/private sector (40%).

Perceptions of the impacts of contaminants on behavior

The overwhelming proportion of respondents agreed or strongly agreed that contaminants "can impact" (97%) and "are impacting" (77%) wildlife. Similarly, although marginally smaller, most respondents agreed or strongly agreed that contaminants "can impact" (84%) and "are impacting" (62%) humans (Figure 1). In both scenarios, when the nuance of the statement changes from "can" to "are," the proportion of respondents who state "neither agree nor disagree" increases, which appears to be driven by a lack of data within this field or, for the second statement, perhaps the knowledge of the respondents, who are primarily ecotoxicologists rather than human toxicologists.

Perceptions of the role of behavioral endpoints in risk assessment

The greatest proportion of respondents disagreed or strongly disagreed (42%) with the statement that behavioral endpoints are currently used in environmental or ecological risk assessment, but 55% agreed or strongly agreed that they are essential (Figure 2). The majority of respondents disagreed or strongly disagreed (63%) that we understand the risks of contaminants to wildlife and human health. However, 68% agreed or strongly agreed that regulatory authorities should consider behavioral endpoints when making decisions over risk, with 78% of respondents agreeing or strongly agreeing that this would likely increase costs to regulators and/or the industry. Interestingly, 54% agreed or strongly agreed that understanding the effects of contaminants on wildlife behavior is critical to protecting human health (28% were neutral). In contrast, 35% of the respondents disagreed or strongly disagreed and 30% were neutral with the statement that behavioral effects are easily linked to standardized apical endpoints and population-level effects.

Perceptions about the utility of behavior studies

Respondents generally considered behavioral experiments to be repeatable (60%), reliable (61%), and relevant (84%). The largest proportion of respondents were more likely to be neutral when asked whether behavioral endpoints are more sensitive (43%), but the majority agreed (80%) that they provide important alternative information to standard regulatory endpoints such as growth, reproduction, and mortality (Figure 3). Respondents were more skeptical when asked whether behavioral endpoints can be easily linked to apical endpoints and population-level effects.

Free-text answers concerning sensitivity from the academia/education group were limited (nine in total). Most of these responses concerned the statement of sensitivity, and these mainly concluded that the degree of sensitivity depends and/or varies, a point also raised by the industry respondents. Some felt that behavioral endpoints can be sensitive but not necessarily more sensitive than other endpoints. For example, behavior was (obviously) perceived as more sensitive than mortality but not necessarily more sensitive than growth and reproduction. "We don't know" was the response from one respondent, suggesting that it may depend on the chemical and its mode of action. Another response was that behavioral endpoints can be used in

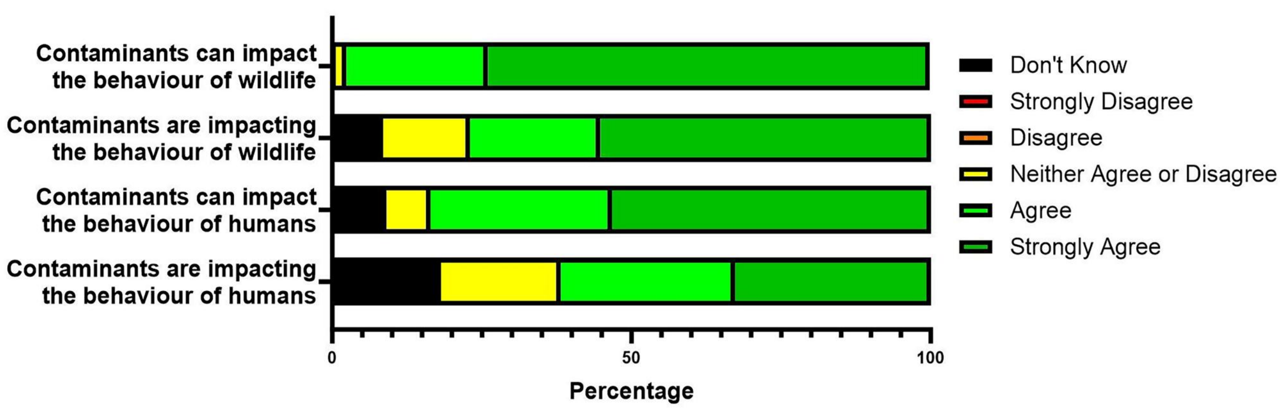

Figure 1. Responses when participants were asked whether they perceived that environmental contaminants "can impact" or "are impacting" humans and wildlife.

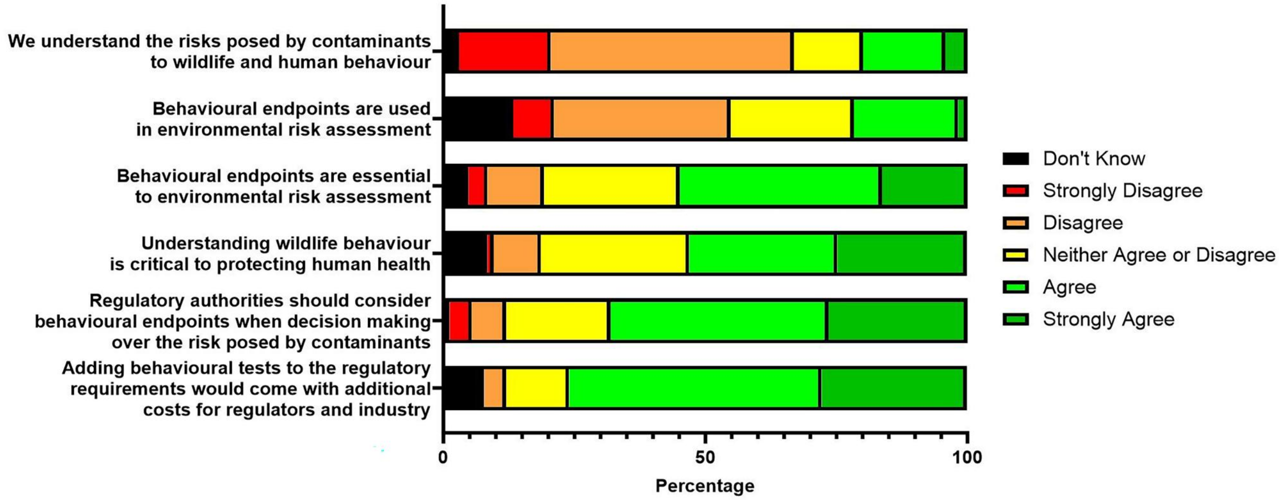

Figure 2. Responses when participants were asked about the role of behavioral endpoints in chemical regulation.

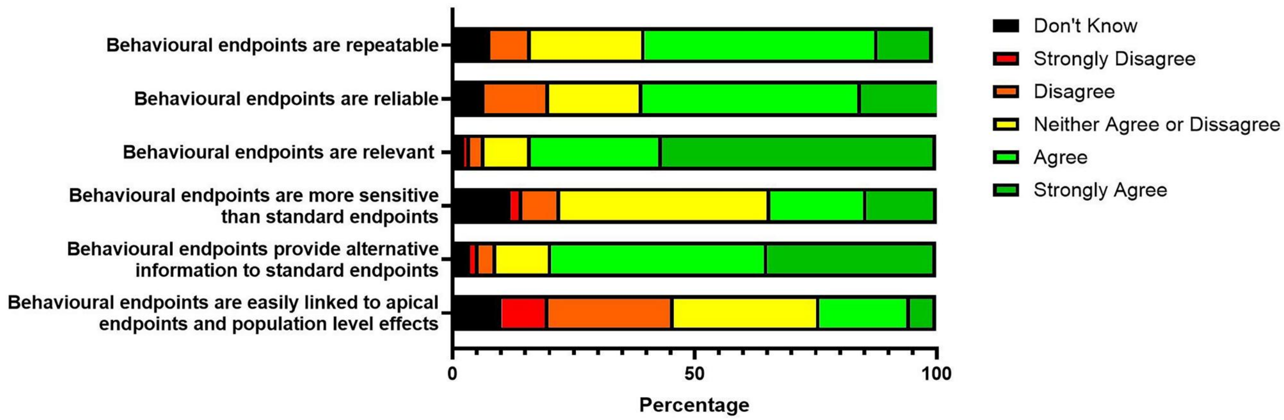

Figure 3. Responses when participants were asked whether they perceived endpoints in behavioral studies to be more sensitive than standard endpoints; whether behavioral endpoints provided alternative information to standard endpoints; or whether behavioral endpoints were repeatable, reliable, or relevant. *Repeatable*: able to be done repeatedly with consistent results. *Reliable*: consistently good in quality or performance. *Relevant*: provides connected and appropriate information for a defined purpose.

addition to, and not as a substitute for, standard endpoints to provide a better picture of toxicity and to identify the mode of action. Three of four respondents from the industry said that it is not possible to say if behavioral endpoints are more or less sensitive, while the fourth would consider them critical if they were reproducible.

Differences between those who do and do not study behavioral endpoints

A higher proportion of academics responding to the survey either work or have worked with behavioral endpoints (67%) as compared with government respondents (48%) and industry scientists (40%; see online supplementary material Table S2). There were no significant differences (Fisher's exact test, $p > .05$) in the responses from those three groups to the statements that contaminants "can impact" and/or "are impacting" the behavior of wildlife and humans, with the majority agreeing with the statement. For all groups, the proportion agreeing with the statement decreases when the form of the statement is changed from "can" to "are" in favor of being neutral or answering "don't know." Most scientists predominantly disagreed with the statement that we understand the risks posed by contaminants to wildlife and human behavior. There was no significant difference ($p > .05$) in the proportions of answers between respondents who do and do not use behavioral endpoints. Similarly, there were no significant differences ($p > .05$) in the proportions of answers for the statement "Behavioural endpoints are used in environmental risk assessment," where respondents were predominantly neutral in their response or disagreed with the statement. The majority of respondents, irrespective of whether they study behavior ($p = .272$), believed that understanding the effects of contaminants on wildlife behavior is critical to protecting human health. However, respondents in the two groups differed in their opinions of the statement "Behavioural endpoints are essential to environmental risk assessment," with those using behavioral endpoints more likely to agree as compared with those who do not, with the latter predominantly answering "neither agree nor disagree" ($p = .0003$). Similarly, there was a significant difference ($p = .004$) in agreement of the statement "Regulatory authorities should consider behavioural endpoints when decision making over the risk posed by contaminants." Whereas both groups predominantly answered in favor of regulatory authorities considering behavioral endpoints, there was a greater proportion of those disagreeing who do not use behavioral endpoints (18%) as compared with those who do (4%). Finally, there was no significant difference ($p > .05$) between the groups with the statement that "adding behavioural tests to the regulatory requirements would come with additional costs for regulators and industry," with the majority of both agreeing.

Some of the largest differences in the responses between those who use behavioral endpoints and those who do not came from the statements about whether behavioral endpoints are repeatable (76% vs. 39% agree, $p < .001$), reliable (76% vs. 42% agree, $p < .001$), and relevant (92% vs. 75% agree, $p = .01$), in addition to whether behavioral endpoints are more sensitive than other endpoints (42% vs. 24% agree, $p = .019$). Across all these statements, those who do not study behavioral endpoints were more likely to be neutral, disagree, or answer that they did not know. There were no significant differences in the proportions of responses ($p = .103$) to the statement that behavioral endpoints provide alternative information to standard endpoints, with the majority agreeing with the statement (85% vs. 72%). Similarly, there were no significant differences in the proportions of responses ($p = .0925$) for the statement that behavioral endpoints are easily linked to apical endpoints and population-level effects. In this instance, those studying behavioral endpoints were more likely to agree (31% vs. 16%), but the proportions of neutral responses and disagreements were fairly evenly split.

There are several possible explanations for the discrepancies between those who study behavioral endpoints and those who do not. First, it may be that those who study behavior are best equipped to answer statements about reliability, relevance, and reproducibility because of their expertise in the field. Those who already work with behavioral endpoints may also feel that the concerns raised by others are not insurmountable. Conversely, those who study behavior may be more likely to be biased in favor of their research field.

Differences across sectors

The survey revealed some significant divergence in the opinions of the respondents from different sectors, particularly those in the industry sector. There were no significant differences in the opinions of respondents among sectors for the following four statements: contaminants "can impact" the behavior of humans (Table 1); behavioral endpoints are used in risk assessment; adding behavioral tests will come with a cost (Table 2); behavioral endpoints provide alternative information (Table 3). For all other statements, there were significant differences among sectors ($p < .05$). Removing industry from the analysis reveals no significant differences between academic and government sectors for any questions ($p > .05$), with more commonality of opinions between these sectors.

There was a high proportion of respondents from all sectors who agreed that "contaminants can impact wildlife behaviour" (academia, 100%; government, 97%; industry, 94%). For the alternative statement "Contaminants are impacting wildlife," the proportion agreeing decreased slightly for academics (91%) and the government sector (77%) but substantially for the industry sector (52%). Industry was more likely to be neutral when faced with the alternative statement that contaminants "are impacting," as opposed to "potentially can impact," the behavior of wildlife or humans.

Many of the respondents from the academic sector (19 responses in total) wrote that there is still much to learn about how and to what extent contaminants affect behavior, but there was a broad consensus that they do. Academics considered behavioral ecotoxicology a relatively emerging field and that more studies are needed. Also, linking effects observed in the laboratory to those in the field was seen as difficult by the academic sector. The subdiscipline is seen as complicated and the risks from contaminants as poorly understood. This response captured some of the issues raised in the free-text responses:

> There is a considerable amount of supporting evidence in the literature that contaminants can and are affecting organisms/wildlife behaviour. There is considerably less evidence for humans, but it is reasonable to assume that they can and are affected. However, understanding the risks is more complicated as behaviour and the mechanisms underpinning it are

Table 1. Survey responses to statements relating to whether contaminants "can impact" and/or "are impacting" the behavior of humans and wildlife.

	Academia		Government		Industry		Fisher's exact test, *p* value	
Survey statements: responses	***n***	**%**	***n***	**%**	***n***	**%**	**All sectors**	**Minus industry**
Contaminants can impact the behaviour of wildlife							.0141	.3009
Agree	79	100.0	33	97.1	43	93.5		
Neither	0	0.0	0	0.0	3	6.5		
Disagree	0	0.0	1	2.9	0	0.0		
Don't know	0	0.0	0	0.0	0	0.0		
Contaminants can impact the behaviour of humans							.5246	—
Agree	66	83.5	30	88.2	36	78.3		
Neither	6	7.6	1	2.9	5	10.9		
Disagree	0	0.0	1	2.9	0	0.0		
Don't know	7	8.9	2	5.9	5	10.9		
Contaminants are impacting the behaviour of wildlife							<.0001	.0215
Agree	72	91.1	26	76.5	24	52.2		
Neither	6	7.6	3	8.8	13	28.3		
Disagree	0	0.0	1	2.9	1	2.2		
Don't know	1	1.3	4	11.8	8	17.4		
Contaminants are impacting the behaviour of humans							.0343	.6074
Agree	56	70.9	22	64.7	20	43.5		
Neither	13	16.5	5	14.7	13	28.3		
Disagree	1	1.3	1	2.9	0	0.0		
Don't know	9	11.4	6	17.6	13	28.3		

Table 2. Survey responses to statements relating to the role and use of behavioral toxicology in risk assessment.

	Academia		Government		Industry		Fisher's exact test, *p* value	
Survey statements: responses	***n***	**%**	***n***	**%**	***n***	**%**	**All sectors**	**Minus industry**
We understand the risks posed by contaminants to wildlife and human behaviour							.0196	.2321
Agree	23	29.1	7	20.6	3	6.5		
Neither	9	11.4	4	11.8	9	19.6		
Disagree	46	58.2	20	58.8	33	71.7		
Don't know	1	1.3	3	8.8	1	2.2		
Behavioural endpoints are used in environmental risk assessment							.1947	—
Agree	16	20.3	5	14.7	13	28.3		
Neither	20	25.3	10	29.4	8	17.4		
Disagree	29	36.7	14	41.2	23	50.0		
Don't know	14	17.7	5	14.7	2	4.3		
Behavioural endpoints are essential to environmental risk assessment							.0022	.9834
Agree	54	68.4	22	64.7	11	23.9		
Neither	17	21.5	7	20.6	19	41.3		
Disagree	4	5.1	2	5.9	15	32.6		
Don't know	4	5.1	3	8.8	1	2.2		
Understanding the effects of contaminants on wildlife behaviour is critical to protecting human health							.0001	.3076
Agree	50	63.3	21	61.8	12	26.1		
Neither	17	21.5	8	23.5	21	45.7		
Disagree	6	7.6	2	5.9	9	19.6		
Don't know	6	7.6	3	8.8	4	8.7		
Regulatory authorities should consider behavioural endpoints when decision making over the risk posed by contaminants							<.0001	.869
Agree	63	79.7	31	91.2	14	30.4		
Neither	13	16.5	3	8.8	17	37.0		
Disagree	1	1.3	0	0.0	15	32.6		
Don't know	2	2.5	0	0.0	0	0.0		
Adding behavioural tests to the regulatory requirements would come with additional costs for regulators and industry							.138	—
Agree	55	69.6	27	79.4	40	87.0		
Neither	11	13.9	6	17.6	3	6.5		
Disagree	6	7.6	0	0.0	0	0.0		
Don't know	7	8.9	1	2.9	3	6.5		

complicated. Add to that that different contaminants cause different effects as well as the question of mixtures.

The main view of the government sector (11 responses in total) is that it is very plausible—sometimes even certain, concerning some risks—that wildlife and/or human behavior is affected by contaminants; however, "our" (government scientists') understanding of this is limited, especially concerning collective contaminants.

The industry sector (15 responses in total) did not, apart from one or two responses, give a straightforward answer but rather questioned the statements, by saying that "impact" is a broad term, that there is a need to define contaminants, or that the statement lacks context and "Is it even possible to formulate a problem to be studied?" Chemophobia is mentioned as an explanation for humans rather than contaminants per se, and existing data are also seen as insufficient. One response was that this is probably not a problem as exposure is low, and another said that it is difficult to say, as behavior (at least human behavior) can be affected by so many things: "Am I tired? Am I hungry? Have I had my coffee?" Such responses highlight the perception that there is a need to determine whether behavioral responses to pollution can be disentangled from day-to-day "feelings," which vary in time and among individuals.

When compared with the other sectors, a greater proportion of the industry sector disagreed with the statement that the risks posed by contaminants to wildlife and human behavior are understood and that behavioral endpoints are essential to risk assessment. Similarly, there was a predominance of disagreement or neutral responses to the statement that behavioral endpoints are used in risk assessment. When the industry sector was removed from the analysis, a comparison between academic and government scientists revealed no significant difference in the proportion of the responses ($p > .05$; Table 2). The respondents from the industry sector were less likely to agree with the statement that behavioral endpoints are more sensitive; instead, a higher proportion were neutral, disagreed, or did not know. There were significant differences in responses among the sectors on the statement that regulatory authorities should consider behavioral endpoints when making decisions on the risk posed by contaminants. The academic (80%) and government (91%) sectors agreed with this statement, as compared with only 30% of the industry sector. The industry sector was more likely to be neutral (37%) or disagree (33%). However, there was agreement across sectors ($p = .138$) toward the statement that the addition of behavioral tests to the regulatory requirements would result in additional costs to regulators and the industry.

The academic sector (11 responses in total) agreed that behavior is relevant and critical and that ignoring behavior as a component of health will "underestimate contaminant impact on

Table 3. Survey responses to statements relating to the reliability, relevance, and sensitivity of behavioral toxicology research.

	Academia		Government		Industry		Fisher's exact test, *p* value	
Survey statements: responses	***n***	**%**	***n***	**%**	***n***	**%**	**All sectors**	**Minus industry**
Behavioural experiments are repeatable							<.0001	.3359
Agree	56	70.9	22	64.7	18	39.1		
Neither	17	21.5	7	20.6	12	26.1		
Disagree	2	2.5	0	0.0	12	26.1		
Don't know	4	5.1	5	14.7	3	6.5		
Behavioural experiments are reliable							<.0001	.2012
Agree	60	75.9	23	67.6	14	30.4		
Neither	12	15.2	7	20.6	12	26.1		
Disagree	4	5.1	0	0.0	16	34.8		
Don't know	3	3.8	4	11.8	4	8.7		
Behavioural experiments are relevant							.0001	.5293
Agree	71	89.9	33	97.1	29	63.0		
Neither	5	6.3	0	0.0	10	21.7		
Disagree	1	1.3	0	0.0	6	13.0		
Don't know	2	2.5	1	2.9	1	2.2		
Behavioural endpoints are more sensitive than standard endpoints (growth, reproduction, mortality)							.0039	.0571
Agree	33	41.8	14	41.2	7	15.2		
Neither	33	41.8	11	32.4	25	54.3		
Disagree	8	10.1	1	2.9	7	15.2		
Don't know	5	6.3	8	23.5	7	15.2		
Behavioural endpoints provide alternative information to standard endpoints (growth, reproduction, mortality)							.226	—
Agree	68	86.1	28	82.4	31	67.4		
Neither	6	7.6	3	8.8	8	17.4		
Disagree	3	3.8	1	2.9	5	10.9		
Don't know	2	2.5	2	5.9	2	4.3		
Behavioural endpoints are easily linked to apical endpoints (growth, reproduction, mortality) and population-level effects							<.0001	.6073
Agree	26	32.9	8	23.5	4	8.7		
Neither	28	35.4	10	29.4	11	23.9		
Disagree	18	22.8	9	26.5	29	63.0		
Don't know	7	8.9	7	20.6	2	4.3		

ecosystems." One respondent wrote that the relevance of behavioral effects on wildlife for human health depends on the situation and concentration, with another writing, "In most cases, one would hope that environmental exposure levels are well below thresholds that could entail effects on humans. Nevertheless, it is prudent to study these potential effects, to be aware of potential risks."

Three of the four respondents from the government sector considered behavioral endpoints to be complementary rather than alternatives to traditional endpoints, such as reproduction and survival. They all supported the use of behavioral endpoints for risk assessment. Responses to whether government scientists use behavioral endpoints for risk assessment varied from not at all to when behavior data are available and relevant.

The industry sector (19 responses in total) took a more critical stand on behavioral endpoints and their use in risk assessment. The reasons for this position varied. Mainly, it seemed to relate to behavioral endpoints being challenging to use in risk assessments, although respondents did not always elaborate on this in the free-text responses. Among the exceptions were those who articulated the lack of clarity in linking behavioral effects to population-level consequences or those who expressed concerns about the endpoints' limited physiological interpretation, which often leads to misinterpretation. Some respondents highlighted that behavioral endpoints provide additional data, but this does not imply that they are useful for risk assessment or are more or less sensitive when compared with other endpoints. For example, one respondent stated,

> The ability to measure "effects" at lower substance concentrations does not make endpoints superior to those unequivocally demonstrated to relate to population-level endpoints. This linkage is critical. We cannot simply allow all "behavioral endpoints" in risk assessment—they must be evaluated individually for true relevance. There are some very good behavioral studies in the literature, but a great many are very poor.

Several respondents indicated that they are "not aware" of evidence of behavioral endpoints and their relevance for protecting ecosystems, wildlife, and human health. Four industry respondents expressed that behavioral endpoints are, or can sometimes be, important or even critical, and three highlighted the need for more studies and method validation before the information could be useful for risk assessment.

There were significant differences among sectors in the responses to whether behavioral experiments are repeatable, reliable, relevant, sensitive, or easily linked to apical endpoints and population-level effects. These significant differences were driven by the variation in responses from the industry sector (Table 3). In each instance, the industry sector was more likely to be neutral or disagree with the statements. For example, 71% of the respondents from the academic sector and 65% of the government sector agreed with the statement that behavioral experiments are repeatable, in contrast to 39% of the industry sector. Similarly, 76% of the academic sector and 68% of the government sector agreed that behavioral experiments are reliable, as opposed to only 30% of the industry sector.

The viewpoint shared by 11 respondents within the academic sector (24 responses in total) is that behavioral endpoints can be repeatable; however, this is not consistent among all behavioral endpoints and studies. Rather, the repeatability of behavioral endpoints depends on the experimental setting, laboratory experiment, or field study, as behavioral endpoints can change according to, for example, life stage, species, external factors, and individualism. One respondent stated, "They cannot always be repeatable but on exact same conditions should be." Measures that are said to strengthen repeatability are strong quality assurance and control, robust and consistent assays, standard methods, and the use of a large-enough sample size. This is suggested to enhance their reliability, as reliability and repeatability are closely connected. In general, behavioral endpoints are seen as reliable if certain conditions are met. The respondents found behavioral endpoints to be relevant, but this was dependent on whether the correct endpoints were selected and if the results were properly interpreted.

The answers from the government sector (12 responses in total) were more cautious concerning the reliability of behavioral experiments and emphasized the importance of experimental design. Behavioral endpoints were seen as relevant in principle, but again, it depends on the selected endpoint and its purpose. Repeatability was considered a challenge, more so than by the academic sector.

The industry respondents (21 responses in total) answered that repeatability and reliability depend on factors such as sample size and whether the study was performed in the laboratory or the field. A couple of the respondents said that there is a lack of accepted test guidelines and that the variability among laboratories is too high to ensure repeatability and reliability. Moreover, behavioral endpoints might not be relevant, as relevance depends on the endpoints being repeatable and reliable, which is not always seen as the case. Overall, this sector was cautious in making firm statements. For example, one respondent stated, "Too much depends on the individual study designs to make such blanket statements."

Discussion

There are several potential reasons why respondents are more skeptical toward behavioral endpoints versus traditional endpoints such as effects on reproduction and survival. The perception of high variability and lack of repeatability in some of these studies may raise concerns about whether the results can be trusted. A number of studies have raised concerns over the repeatability of widely used behavioral tests with rodents (Knab et al., 2009; Rudolfová et al., 2022). Rosso et al. (2022) found anxiety-based tests in mice for drug design to be unreliable. They conducted a systematic review of 814 studies reporting the effects of 25 anxiolytic compounds using common behavioral tests for anxiety. They concluded that only two of the 17 commonly used test protocols reliably detected the effects of anxiolytic compounds, with high variability among studies and in the direction of the effects. They also reported on those behavioral tests' general lack of sensitivity, which they believe cast "serious doubt on both construct and predictive validity of most of these tests," and they subsequently "call for a revision of behavioural tests of anxiety in mice and the development of more predictive tests" (Rosso et al., 2022). However, given that industry uses behavior in drug design, it needs to be noted that there is not a complete mistrust in behavioral endpoints by the regulated community (Dash & Patnaik, 2023; de Abreu et al., 2021). Furthermore, researchers have highlighted that through better experimental designs, choosing the correct endpoints and fully understanding the animal model's baseline behaviors can mitigate issues of repeatability (Langen et al., 2011; Rudeck et al., 2020). Yuen et al. (2016) explored whether a series of classic behavioral tests (activity, boldness, exploration, and aggression) using mouse models could be replicated between the laboratory and field. They reported that all personality traits were highly repeatable and consistent within and between the laboratory and field experiments. Our study did not differentiate the type of industry or role within industry to any degree, which might have helped provide more resolution to why this sector is more skeptical than others.

The lack of behavioral endpoints in internationally validated standardized tests (e.g., by OECD) reduces their acceptability in regulatory settings (Ågerstrand et al., 2020) and may be more resource intensive to evaluate as the test design may be unfamiliar to the assessor. This may affect the willingness of the industry to conduct behavioral studies, as they are not consistently required and thus may not aid in meeting regulatory requirements. Toxicity testing is costly, especially chronic studies of longer duration. If behavioral studies were added to the testing requirements of regulation or risk assessment, this would increase costs for the industry sector. For example, Schlander et al. (2021) estimated that the costs to bring a new drug to market in 2019 were between $161 million and $4.54 billion, although arguably these were greatly reduced through more high-throughput screening of favorable or unfavorable (addictiveness) behavioral outcomes via laboratory models. However, advancing the scientific understanding of behavioral (eco)toxicology could result in the development of reasonable uncertainty factors for application within risk assessments.

The practice in chemical risk assessment is that the most sensitive endpoint in the dataset is used as key evidence when setting guidance values. Adding more sensitive endpoints, for example, from a behavioral study, will lower the guidance value, thus increasing the estimated risk. This in turn may lead to more stringent risk management measures, such as a classification, a restriction on how and when a chemical can be used, or even a complete ban. In other words, there may be a direct economic impact for a chemical company if more sensitive endpoints, such as behavior, are included in risk assessments, making those industries less apt to approve of such an approach (Goldberg & Vandenberg, 2019; Legg et al., 2021; Schäffer et al., 2023). Yet, academic and government sectors may be more receptive to more sensitive endpoints for environmental reasons and not driven by financial implications. It could also be argued that given the human health and environmental costs of chemical contaminants, not adding behavior to the suite of tools to assess chemical safety comes with cost.

The majority of respondents agree that environmental contaminants with behavioral effects can affect the health of wildlife and humans. The strength of this agreement was lower when the alternative statement asked "are" as opposed to "can." Respondents were more neutral when responding to the statement of whether behavioral endpoints are more sensitive than standard endpoints, partly because respondents felt that this still needed to be determined or was likely to be dependent on the contaminants under review. However, they did believe that behavioral endpoints provide alternative information for a better understanding of either the mechanistic effects or ecological consequences of contaminated ecosystems. This perhaps underlines the stronger support for the statement that behavioral endpoints were relevant as compared with repeatable and reliable. Some felt that this was particularly important when agreeing that behavioral testing would come with greater financial burdens to regulatory authorities and/or industry. Similarly, respondents generally considered risks to human health and the environment to not be fully understood, and there is a need to integrate behavioral endpoints into risk assessments and regulation. This survey primarily surveyed scientists of environmental societies. Therefore, we likely received responses from ecological-focused scientists instead of human health-focused toxicologists, suggesting that a follow-up study of human health scientists would make an interesting comparison.

Clearly, the decision to include behavioral endpoints as measures of effect specifically linked to assessment endpoints and corresponding environmental protection goals requires careful consideration during problem formulation at the beginning of the risk assessment process (Suter, 2023). Across all sectors, when questioned on reliability and repeatability, scientists mentioned the importance of experimental designs and baseline data, and they fully understood behavioral endpoints. Efforts are already underway to improve the reliability and repeatability of behavioral ecotoxicology. For example, EthoCRED was recently published as a framework to guide reporting and evaluation of the relevance and reliability of behavioral ecotoxicity studies (Bertram et al., 2025). The EthoCRED method was designed as an extension of the CRED project (Criteria for Reporting and Evaluating Ecotoxicity Data; Moermond et al., 2016) and can be readily implemented into regulatory frameworks to allow better integration of knowledge gained from behavioral testing into environmental protection. New OECD test guidelines typically take many years to develop and receive intergovernmental approval; however, modification of existing OECD guidelines is considered a shorter optimal path forward where existing protocols could have behavioral endpoints recorded during or at the end of existing apical tests (Ford et al., 2021). For example, in their review of the OECD test guidelines relevant to environmental assessment, Polcher et al. (2023) identified a number of guidelines that could be adapted to include behavior. Yet, bespoke species and endpoints may well need to be developed, as common laboratory models may not display novel, optimal, and/or quantifiable "behaviors" for assessment (Ford et al., 2021).

To move forward with the regulatory use of behavioral endpoints, a number of issues need to be clarified. There seems to be no legal barrier to the use of behavioral endpoints in risk assessment in European Union chemical regulation (Ågerstrand et al., 2020), and this is most likely the case in other regions. Globally, there are few standardized test requirements (i.e., mainly for bees) for behavioral endpoints in chemical regulation. Industry is therefore unlikely to carry out such studies to any significant extent when a regulatory requirement does not exist. If the test requirements are not updated, most of the behavioral studies will be produced by academia. These studies cover only a small number of substances, and systematic coverage cannot be expected. The inclusion of these studies in risk assessment depends on whether industry or regulators are aware of the study. According to European Union chemical regulation, a systematic search of the literature should be carried out, and all studies of sufficient reliability and relevance should be included in the risk assessment; however, this has not always been done. The European Commission therefore stressed in the Chemicals Strategy for Sustainability (European Commission, 2020) that improvements are needed, but it remains to be seen what measures will be taken. The real and perceived variability and problems with the reliability and reproducibility of behavioral studies could prevent their use in risk assessment. This issue needs to be addressed in all jurisdictions through a collective effort by researchers, funders, and scientific journals (e.g., Polcher et al., 2023). The discussion on the relevance of behavioral endpoints for the survival and health of a population needs to be continued to ensure that studies that protect wildlife are included in worldwide decision making (Ågerstrand et al., 2020; Ford et al., 2021).

Supplementary material

Supplementary material is available online at *Integrated Environmental Assessment and Management*.

Data availability

The data are available upon request.

Author contributions

Alex T. Ford (Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing—original draft, Writing—review & editing), Marlene Ågerstrand (Formal analysis, Investigation, Writing—original draft, Writing—review & editing), Natasja Börjeson (Formal analysis, Investigation, Writing—original draft, Writing—review & editing), Tomas Brodin (Investigation, Writing—original draft, Writing—review & editing), Bryan W. Brooks (Investigation, Writing—original draft, Writing—review & editing), Gerd Maack (Investigation, Writing—original draft, Writing—review & editing), James M. Lazorchak (Investigation, Writing—original draft, Writing—review & editing), Minna Saaristo (Investigation, Writing—original draft, Writing—review & editing), and Bob B. M. Wong (Investigation, Writing—original draft, Writing—review & editing)

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Conflicts of interest

The authors declare that they have no competing interests.

Ethical statement

This study was reviewed and approved by the Science and Health Faculty Ethics Committee at the University of Portsmouth (SHFEC 2023-052). No personal identifiers were recorded during this survey.

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The views expressed in this article are those of the authors and do not necessarily reflect the views or opinions of their institutions. The mention of trade names or commercial products does not constitute endorsement or recommendation for use. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government. The peer review for this article was managed by the Editorial Board without the involvement of Marlene Ågerstrand.

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