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Perspective

Ocean for Health: A Transdisciplinary Framework to Accelerate Research on Ocean–Human Health Connections

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ABSTRACT: The ocean has an important impact on human health. Observational studies suggest that ocean-related stimuli can improve human health, but there is limited research investigating the underlying mechanistic and epidemiological principles. Research on the interactions between the ocean and human health remains fragmented, leading to a patchy understanding of these complex connections. To structure and advance research on interactions between the ocean and human health, a transdisciplinary framework is proposed comprising of four key components: (a) ocean stimuli originating from the hydrosphere, atmosphere, lithosphere, biosphere and anthroposphere, (b) time, location, and behavior dependent human interaction with these stimuli, (c) individual sensing and processing of ocean stimuli, and (d) health outcomes at individual and population level. In addition to the introduction of this framework that builds on and integrates previous theories, we discuss how its application can promote the protection of marine environments, thereby indirectly safeguarding the mechanisms that underlie ocean–human health connections. The proposed framework makes explicit a transdisciplinary approach of OHH research and contextualizes future studies.

KEYWORDS: *blue spaces, health benefits, nature and health, ocean stimuli, Ostend working group*

1. INTRODUCTION

The ocean has long been associated with human health benefits and a general sense of wellbeing.[1,2] Epidemiological studies confirm that living near blue spaces, defined as outdoor areas where water is a central feature,[3] positively impacts overall human health.[4−6] Ocean health effects are often attributed to for example increased physical activity,[7] more social interactions,[8] improved psychosocial state,[1] and exposure to bioactive compounds and microbiota in sea spray aerosols.[9,10]

Despite multiple historical and cultural remnants, such as sea sanatoria and thalassotherapy centres that proclaim an intrinsic positive connection between human health and the ocean,[11,12] we still lack comprehensive, evidence-based mechanistic and epidemiological understandings for these health effects. Most ocean and human health (OHH) related research has been largely conducted on an *ad hoc* basis. Studies are often initiated independently, without a structured, cohesive plan or coordinated effort across the OHH field. The fragmented nature of this research approach can result in knowledge gaps, duplicated efforts, and difficulties in effectively synthesizing and applying findings.[13] As such, many studies showing health benefits of ocean interactions are small-scale, building on local knowledge, experiences and opportunities.[1] While these studies provide useful information, it is unclear how these place-based outcomes can be applied to other locations and populations.[14] Current OHH research also tends to be too much discipline-specific, failing to capture the complexity of the interactions between the ocean and humans. Addressing health-related challenges inherently demands a transdisciplinary approach.[15]

In recent decades discipline-specific studies have explored the links between ocean health and human health.[13] However, recently, also overarching initiatives and research projects have created momentum for a more integrated approach to OHH research. One of the first cross-border European initiatives to compile the strategic needs for interdisciplinary OHH research was the corresponding position paper of the European Marine Board,[16] building on the foundations of the blue gym hypothesis.[17,18] This position paper emphasized that human

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health is intrinsically connected to the health of the ocean. The current state of OHH research has been reviewed[13,19] and the key policy needs have been summarized in a policy brief of the European Marine Board.[20] The H2020 SOPHIE Consortium[21] built on this foundation and made significant progress in structuring OHH research. Interactions were described along three areas, being (1) sustainable seafood and healthy people; (2) blue spaces, tourism and wellbeing; and (3) marine biodiversity, biotechnology and medicine. In parallel, cross-country knowledge was generated through the H2020 Blue-Health project.[22−24] In addition to defining a strategic research agenda,[21] due to the complexity of the interactions found, the need for the inclusion of both positive and negative OHH interactions was emphasized.[25] For example, it has been accentuated that marine biodiversity loss has direct and indirect effects on human health.[26] A direct consequence is the reduction of the genetic resources that could be explored for future medicines.[27−29] A more indirect effect of species loss may result in less diverse bioactive stimuli that are sprayed toward coastlines,[30] and as such people are interacting with lower doses of these bioactive compounds.[31] Although such location-specific results have been reported[28,32] further quantitative research focusing on blue spaces are recommendable.[26,33] Beyond the toxicological and pharmacological approach, there is also growing interest in the transdisciplinary field of psychology and marine ecology. A growing body of empirical evidence is revealing the value of nature experience for mental health.[34] However, it remains largely unquantified to what extent a healthy and diverse ocean contributes to improved resilience and psychological health. Another complex OHH interaction that still could be further uncovered, relates to physical activity and social interactions. For example, open water swimming combined with the social aspects of group swimming enhance participants' health and wellbeing.[8] However, as with many aspects of OHH, more robust evidence is needed before open water swimming may become a viable mental health intervention.[35] These examples in which often fragmented first indications have been revealed but underlying mechanistic and epidemiological principles remain patchy, underscore the inherently transdisciplinary nature of ocean−human health connections. To move beyond discipline-specific studies, it is increasingly clear that a transdisciplinary OHH framework is needed to better contextualize OHH interactions and stimulate integrated transdisciplinary research.

Human health fundamentally depends on a thriving ocean,[32,36] the mechanisms underpinning these interactions are complex, and disciplinary boundaries continue to challenge integration. To overcome these obstacles, a more systematic and coordinated research approach is essential. The transdisciplinary OHH framework introduced here builds upon and integrates insights from existing frameworks and paradigms. It is not intended to replace them but rather to complement and extend them, offering a dedicated structure for advancing the science and policy of OHH. The OHH framework is essential because it uniquely integrates marine sciences, biological, psychological, and social health sciences to assess both the positive and negative health impacts of ocean stimuli. These are research fields that alternative frameworks either only partially address or do not cover. Concepts like ecosystem services, planetary health, One Health, and Drivers, Pressures, State, Impact, Response (DPSIR) framework provide insights into environmental health, but none fully capture the distinct biophysical, chemical, and socio-cultural dimensions of the ocean. These frameworks generally do not systematically examine how ocean stimuli influence human health across multiple pathways. The concept of ecosystem services categorize what the ocean provides,[37] and building upon that, the OHH framework tells us how those provisions directly affect human health, both positively and negatively. While the planetary health concept provides a broad global context,[38] the OHH framework provides a structure for the underlying mechanisms and pathways for how the ocean influences human health. As such, the OHH framework is not separate from the planetary health concept, but rather a subfield within it. However, its distinct biophysics and chemical unique characteristics, unique socioeconomic and cultural dimensions, and ocean-specific health interactions makes it substantial enough to warrant its own dedicated framework, separate from, yet complementary to, planetary health. The OHH framework and One Health concept share common principles of environmental health, but have different focal points. One Health is centered on human-animal interactions and disease control.[39] Both concepts are complementary in fields such as marine zoonoses, seafood safety, and climate-driven disease shifts, but clearly distinct as one health does not fully capture the unique aspects of ocean−human interactions. Though both are used in environmental science and policy, the OHH and the DPSIR[40] frameworks serve different purposes. The exposome framework conceptualizes how environmental exposures affect physical health throughout lifespan,[41] but has no focus on social and psychological dimensions.[42] Other frameworks, like the research and monitoring framework developed by Knap et al.,[43] view the ocean as an "environmental soup" of contaminants, primarily focusing on ecosystem change and its threats to human health. The nature-based biopsychosocial resilience theory offers a broad framework for understanding nature-human health interactions,[44] but does not specifically address the ocean. Therefore, a transdisciplinary OHH framework that provides a holistic view by integrating biological, psychological, and social health dimensions from ocean interactions is essential for establishing consensus on terms and definitions, facilitating cross-disciplinary knowledge integration and exchange.[25] This framework aims to unify and gives context for future OHH research. Such framework will facilitate science-policy communication and will pave the way toward more integrated and holistic policies.

The Ostend Working Group (OWG) on OHH is a philanthropy-based research network that brings together 21 scientists from Belgian institutions representing 15 scientific disciplines, including bioscience engineering, chemistry, (eco)-toxicology, environmental engineering, environmental epidemiology, food sciences, marine biology, medicine, microbiology, pharmacology, physiology, psychology, epidemiology, sociology, and exercise and environmental physiology. During three workshops in spring 2023, spring 2024, and autumn 2024, it was discussed how ocean health relates to human health, framing our discussions within the context of the Sustainable Development Goals (SDGs) of the United Nations (UN), particularly SDG14 which asserts that "*Healthy oceans and seas are essential to human existence and life on Earth*", and SDG3 which aims to "*Ensure healthy lives and promote wellbeing for all at all ages*".[45] There was consensus in the OWG on the intrinsic positive connection between ocean health and human health. The lack of sufficient quantification and understanding of the mechanisms driving the ocean−human health connection, coupled with the complex interplay between human benefits and threats to ocean health,

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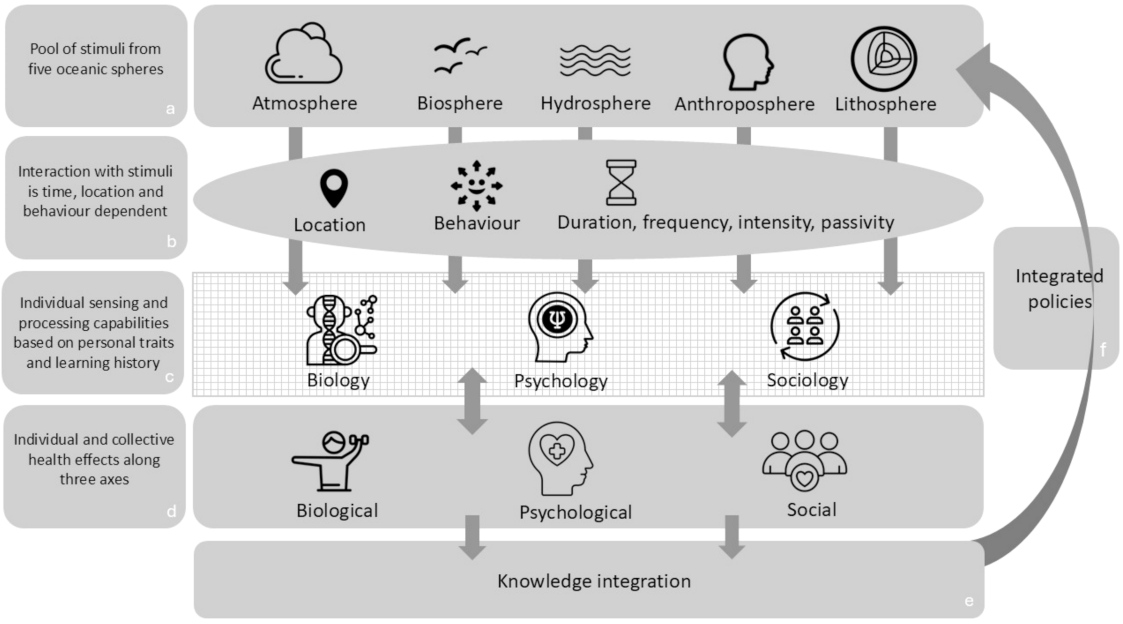

Figure 1. Four key components of the transdisciplinary Ocean and Human Health (OHH) framework: (a) ocean stimuli; (b) interaction with ocean stimuli; (c) individual sensing and processing; and (d) individual and collective health outcomes. Increased awareness through transdisciplinary knowledge integration (e) facilitates shaping integrated policies (f).

underscores the need for a new transdisciplinary OHH framework.

2. AIM OF THE OHH FRAMEWORK AND KEY DEFINITIONS

A transdisciplinary OHH framework based on uniform terminology and definitions should serve as a guide to research, and function as an integrating tool that helps researchers to bring multiple aspects of OHH together.[46] The transdisciplinary OHH framework should create context and coherence to the field, outlining key disciplines and providing an overarching structure for understanding, analyzing, and interpreting the OHH connections. It should also connect findings from isolated studies, offering a comprehensive view on OHH interactions. The framework should further serve as a roadmap, guiding researchers in formulating hypotheses, designing research, interpreting discipline-specific results in a broader transdisciplinary context, and performing meta-analyses and reviews. Below, we define the three key-players of the framework: ocean, ocean health, human health.

The ocean encompasses five spheres: the atmosphere, biosphere, hydrosphere, anthroposphere, and lithosphere.[47] Above the ocean, the oceanic atmosphere carries moisture, bioactive molecules, microbiota, natural particles, and salts. Aerosolized substances from the sea surface microlayer and terrestrial ecosystems (e.g., sand and vegetation) contribute to atmospheric processes, emphasizing the interconnectedness of the five spheres. The biosphere includes all living matter in the ocean, in the air, and on the adjacent land. The biosphere spans from microscopic organisms to marine mammals, exemplifying the rich biodiversity inherent in the ocean. Within the oceanic hydrosphere lies not only the expansive body of water, but also dissolved gases, salts, minerals, and vital nutrients. The oceanic anthroposphere includes all people living permanently or temporarily near the coast and includes coastal communities and temporally visitors. Human-induced pollutants, such as NO_x, SO_2, (nano- and micro)plastics, toxic metals, and persistent organic pollutants (POPs), including perfluorinated alkyl substances (PFAS), are identified as components of the anthroposphere, even when these pollutants are in fact present in one or more other spheres.[48] Finally, in the ocean, the lithosphere encompasses the seabed, seafloor, and deeper geological layers and everything that may be contained within these layers, such as gas and oil. Beaches and dunes are part of the lithosphere, serving as interfaces between the oceanic and terrestrial ecosystems.

There is currently no consensus on an universal definition concerning the health of the ocean, here referred to as ocean health.[49] In the view of the OWG, key aspects in the ocean health definition relate to biodiversity, ecosystem functionality, and the quality of marine environmental compartments. As such, we follow the United Nations,[50] interpreting the term ocean health as a metaphor, a nonlocalized indicator that aggregates across various system components. This means that ocean health is more than the sum of its parts; it is an overarching property that emerges from the interactions and relationships among its components. The UN considers the ocean healthy if it can support biodiversity, regulate climate, provide food and livelihoods, resist pollution and damage, maintain stable ecosystems, and recover from human impacts.

Human health was defined by the World Health Organization as "a state of complete biological, psychological, and social well-being and not merely the absence of disease and infirmity".[51] However, over time, the definition of health has evolved and recent understandings have approached health as a complex adaptive system and focus on resilience and capacity to self-manage in the face of social, biological and psychological challenges. Health is considered to be a dynamic, is not fixed nor absolute, and is constantly responding to environmental, social, biological, psychological conditions or states.[52]

3. DESCRIPTION OF THE OHH FRAMEWORK

The proposed OHH framework is built around four key components: (a) ocean stimuli; (b) interaction with ocean

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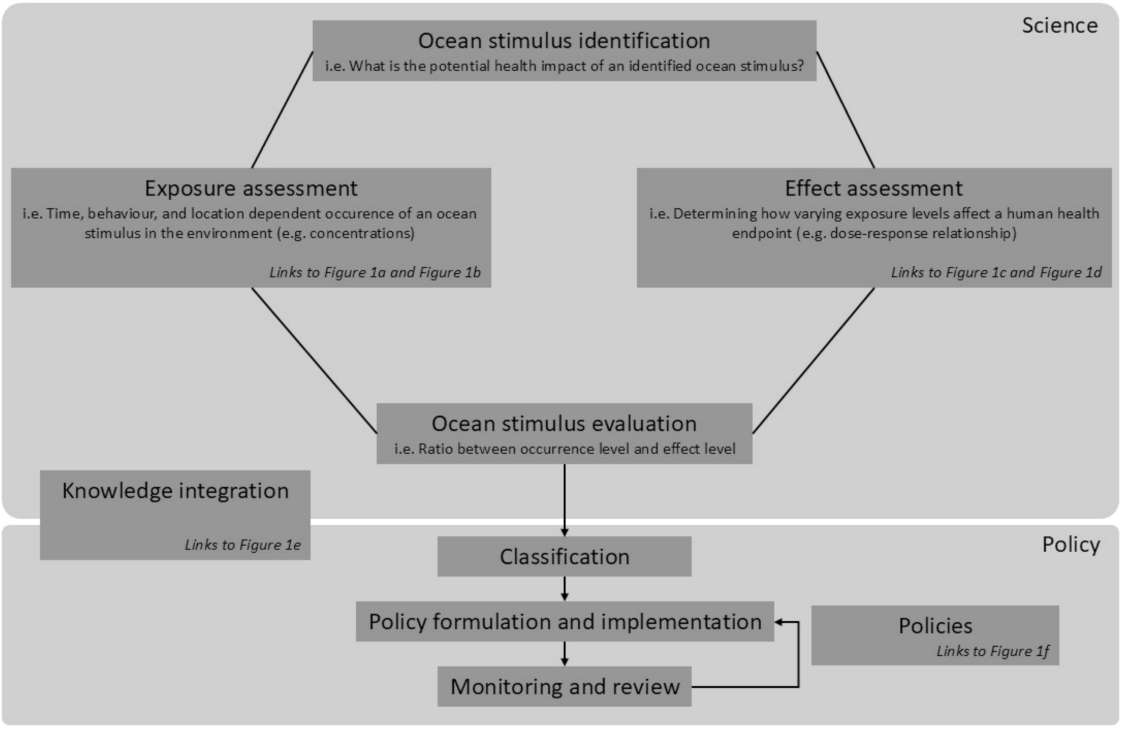

Figure 2. Ocean stimuli assessment in four scientific steps: ocean stimulus identification, exposure assessment, effect assessment, and ocean stimulus evaluation. Objective scientific findings are integrated in one ratio and used to inform the policy decision making process.

stimuli; (c) individual sensing and processing; and (d) individual and collective health outcomes (Figure 1). This framework begins with the premise that individuals, depending on time, location, and their behavior are exposed to and interact with stimuli originating from the five oceanic spheres: atmosphere, biosphere, hydrosphere, anthroposphere, and lithosphere. Ocean stimuli from these five spheres include a range of elements, such as aerosolized bioactive molecules,[9] sounds,[53] odors,[54] nutrition,[55] views,[56] physical activity,[6] and social interactions.[2] Individual responses to these stimuli are influenced by genetic, cultural, social, and demographic factors, as well as the duration, frequency, intensity, and passivity of the interactions.[14] Each person has an unique filter shaped by their individual biopsychosocial traits and learning history, affecting their receptiveness to and processing capabilities of ocean stimuli. The combination of individual receptiveness and processing capabilities leads to personal health outcomes, resulting in varied responses even among those exposed to the same dose of stimuli. This nondeterministic impact, where effects depend on individual characteristics, underscores the complexity of the ocean−human health relationship. People experiencing health effects may even adapt their behavior and as such increase their interactions with oceanic stimuli. The plurality of individual responses and its collective outcome shapes the overall health status of a community or population along three axes of health (i.e., biological, psychological, and social; Figure 1). Due to the individual-level variation,[26] the health of a population is not necessarily the sum of individual's health.[57]

This OHH framework is designed to support scientists, the public, and policymakers in investigating the intrinsic connection between ocean and human health. By raising awareness of this, it fosters also a deeper understanding of how both individual and collective actions impact marine environments − and, in turn human health because we risk disrupting or losing vital mechanisms that support the ocean−human health connection (Figure 1). This holistic approach maximizes respect and care for the oceanic spheres for example via integrated policies, ultimately leading to healthier ecosystems and communities. The latter is illustrated by the feedback loop from the knowledge obtained to the five ocean spheres (Figure 1). The policy feedback loop is important, because besides the health in all policies aspiration,[58] OHH has not been explicitly incorporated into global ocean governance frameworks.

The OHH framework could be relevant for ongoing developments in ocean governance. The Law of the Sea and Small Island Developing States (SIDS) are actively using the UN Convention on the Law of the Sea (UNCLOS) to argue for ocean-based climate action, linking ocean degradation to human health impacts. In this context, the OHH framework can help structuring quantified health effects of ocean change, providing evidence for legal claims. There is growing momentum to grant the ocean legal personhood to strengthen protection efforts.[59] If the ocean becomes a legal entity with rights, this could fundamentally change how we approach marine conservation and public health.[60] Also, via the European Oceans Pact, the European Commission is setting up a vision for a holistic approach to ocean-related policies. The Oceans Pact aims to bring coherence across EU policy areas related to the ocean.[61] In this context, the OHH framework can again contribute by structuring results and establishing a common OHH lexicon. Future efforts should focus on formalizing OHH metrics within international governance frameworks, ensuring that the connection between ocean and human health is explicitly reflected in environmental and public health policies. The OHH framework is designed to be a key tool for advancing science-informed and evidence-based policy and decision-making.

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4. RISK-BENEFIT INTEGRATION

The OHH framework builds further on the recommendations formulated by Borja et al.[13] and the SOPHIE strategic research agenda.[21] Both documents rightfully state that OHH research is fragmented and call for interdisciplinary collaboration. In this manuscript, we propose a potential solution to this fragmentation by introducing a structured research model that enables systematic collaboration across disciplines, ensuring that their work is both comparable and integrative. We provide a framework for, and a lexicon that can be used by different scientific disciplines, including bioscience engineering, chemistry, (eco)toxicology, environmental engineering, environmental epidemiology, food sciences, marine biology, medicine, microbiology, pharmacology, physiology, psychology, epidemiology, sociology, and exercise and environmental physiology. Based on the framework we can speak the same language, collaborate in a systematic way and move toward quantified data on top of qualitative information.

By distinguishing ocean stimuli (key components Figure 1a,b) from effects (key components Figure 1c,d), as per Morris et al.,[62] the framework enables a systematic evaluation of the potential risks and benefits associated with the ocean stimulus of interest (Figure 2). Borrowed from (eco)toxicology, the environmental risk paradigm can be used to perform risk/benefit analyses, which includes four steps: ocean stimulus identification, exposure assessment, effect assessment, and ocean stimulus evaluation.[63] Here, we exemplify the risk/benefit assessment of immunostimulatory compounds found in sea spray aerosols.[10] In step 1, we identified the immunostimulatory compounds present in sea spray aerosols as being potentially healthy. In step 2, exposure data are observed at the ocean spheres and allow quantification of ocean stimuli that people interact with. It is anticipated that the ambient concentrations of the ocean stimuli are location, time, and behavior dependent. In step 3, as in (eco)toxicological research, the effect assessment focuses on determining how varying doses of the ocean stimuli affect a specific health end point. This can be investigated through various study designs, from laboratory-based studies to real life exposures, often with the goal of developing dose and time response relationships. From these dose−response relationships threshold value can be identified indicating the concentration at which the immunostimulatory compound has an influence on the human health. In step 4, in the ocean stimulus evaluation, exposure and effect data are integrated by calculating the ratio between ambient concentrations and the effect level (Figure 2). So, by making the ratio of the ambient concentration of the bioactive compound under study with the threshold value as of which health effects can happen, one can quantify the probability that health effects occur.

The uniqueness of the OHH framework and overlap with the risk-benefit paradigm is that none of the existing concepts and theories,[37−44] to the best of our knowledge, have developed a framework to quantitatively assess effects of ocean stimuli in both potentially positive (benefits) and negative (risks) directions in a transdisciplinary manner. Being integrative for positive and negative impacts is important as, at present, research on positive health outcomes totals roughly half that of potentially negative ones.[18]

The OHH framework is expected to play a crucial role in standardizing joint observations of ocean health and human health. The long-standing discipline-specific focus has resulted in fragmented data sets, inconsistencies in units, and barriers to transdisciplinary research. By offering a structured and integrative approach, the OHH framework will facilitate observation networks in the collection of ocean and human health data in a harmonized manner, improving the comparability of findings. This standardization is essential for strengthening evidence-based policy. The OHH framework can help to the identification of appropriate observation techniques, units and metrics as it addresses both the exposure and effect component of ocean stimuli.

Development of dose−response relationships is essential for nature-based therapy as it clarifies how stimuli trigger specific health end points. In the RESONATE project[64] for example, optimal levels of nature exposure are being determined by examining factors such as frequency, duration, and type of nature interactions across various demographics and settings. Based on this information practitioners can tailor effect evidence-based nature prescriptions. An important remark is that one ocean stimulus often triggers interacting mechanisms. As such, a remaining challenge is on how to assess the combined effect of ocean stimuli. In parallel with (eco)toxicological work it, is anticipated that a combination of stimuli will result in an additive, synergistic or antagonist joint effect.[63] However, clarity about which stimuli are key and what weights of effects to be attributed to each stimulus remains to be studied.

5. APPLICATION

To demonstrate the practical application of the OHH framework, we explored the health effects of a day trip to the Belgian North Sea. A day trip is defined as an activity of at least 1 h outside one's own municipality without an overnight stay.[65] The OHH framework provides a structured approach to assess human interactions with the ocean, considering different exposure pathways, environmental conditions, and human health responses.

A visit to the Belgian coast involves engagement with a wide range of ocean stimuli, whether through active participation in activities such as walking, swimming, eating, drinking, and playing beach games or through passive interactions such as breathing in sea air or gazing at the horizon.[66] Each of these experiences brings an individual into contact with multiple environmental factors from the five oceanic spheres, including water, sand, air, wildlife, and other visitors. The nature and intensity of these exposures vary according to the type of activity, its duration, and the specific environmental conditions at the time. Walking along the beach, for example, offers a clear physical dimension that can stimulate cardiovascular health and engage different muscle groups,[67] and the level of exertion differs depending on whether one is walking on soft sand or a paved surface. At the same time, the social nature of such activities can influence emotional health, as social interactions with friends, family, or even unknown persons contribute to a sense of connection.[68] The psychological dimension of a coastal visit is also shaped by (passive) interactions with the environment. Gazing at the horizon, feeling the wind on the skin, and listening to the waves can support mental restoration. However, these benefits are context dependent. Factors such as the amount of people or pollution[69] can influence the expected health-promoting effects of the coast. Additionally, personal memories and emotional associations with coastal environments - such as childhood experiences or significant life moments - can be expected to shape how individuals perceive and respond to these settings, potentially enhancing or diminishing their restorative impact. Visitors to the Belgian coast are also exposed to a range

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of atmospheric, marine particles through inhalation or skin contact. These include marine aerosols that may carry bioactive compounds, but also pollutants, such as nano- and microplastics, toxic chemicals, and toxins from harmful algal blooms.[70−72] Such exposures can have positive or negative health effects, depending on concentration, dose, and duration. For instance, certain bioactive compounds in sea spray have been hypothesized to support immune function, whereas airborne toxins from harmful algal blooms may present respiratory health risks. The OHH framework captures these complex and interrelated processes, emphasizing how human health outcomes depend on both environmental quality and individual variable responses.

The OHH framework serves as a tool to investigate OHH interactions and has direct relevance for policy and regulation. The presented application case highlights also key areas where OHH research can inform policy decisions. Marine pollution and human exposure to contaminants such as microplastics, PFAS, and harmful algal toxins could raise concerns about recreational health risks. Existing environmental policies, such as the EU Water Framework Directive[73] and Marine Strategy Framework Directive,[74] primarily focus on ecosystem health, but the human health dimension remains underexplored. Expanding observation efforts to link marine pollution data with human exposure metrics would ensure that visitors are protected and fully benefit from ocean stimuli.

By considering the biological, psychological, and social dimensions of ocean stimuli, and recognizing individual differences, we can comprehensively study the health impacts. This structured approach, as proposed by the OHH framework, ensures a holistic view of the interactions between the ocean and human health and will facilitate the mechanistic and epidemiological understandings of the ocean−human health connections. Future research should prioritize the standardization of OHH indicators, ensuring that human health considerations are embedded within marine governance frameworks.

6. IMPLICATIONS

The OHH framework allows a holistic view on OHH research and integrates findings and perspectives from social sciences, life and health sciences and biological sciences into a transdisciplinary approach. Moreover, the OHH framework offers researchers a global OHH context and a systematic research approach that facilitates the harmonization of ad hoc research questions and associated hypotheses toward the shared objective of understanding the pivotal role of the ocean on human health. The OWG on OHH anticipates that unravelling causal mechanisms and communicating these will pave the way toward a better integration of health policy in all policies.

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Notes

The authors declare no competing financial interest.

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