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Built environment as interface: a relation-based framework for the intersections between built, biotic, social, and health processes during COVID-19 and beyond

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By broadening disciplinary perspectives to architecture and design, philosophy of science, and systems biology, this paper aims to explore the interconnections between built, social, biotic, and health processes with key attention to the moderating roles of the built environment. The focus is part diagnostic and part prescriptive. Initially, we specify failures in COVID-19 representational infrastructure and practice in accounting for built environment and social process impacts on public health factors. By presenting three intertwined problems with scientific representation in COVID-19 modeling and data-gathering, we examine to what extent current scientific practices fail to robustly account for the complex *intersections* between built, biotic, social, and health processes. We suggest that resolving the presented problems requires the development of new conceptual precedents for the analysis of causal *relations* in changing contexts. The second focal point is prescriptive. By discussing conceptual developments that spotlight relations—e.g., ‘context’, ‘nudge’, ‘affordance’, and ‘interface’—we organize the numerous moderating roles of built environment contexts, and we suggest practical applications to ongoing public health practices—such as, cautioning against nudge policies. Ultimately, we argue that the built environment can be represented not only as a single variable (or handful of discrete variables) but also as an *interface* that reorganizes multiple causal landscapes—concurrently, deregulating factors and leaving others unaffected. Because of the difficulty of representing emergent properties, relevant to differential built environment burden and inequitable health outcomes, we provide ways to visualize the built environment as interface in multidimensional form. We conclude that adequately representing the various moderating roles of the built environment goes a step beyond *how* to represent complexity, and it requires asking a deeper normative question: *who* ought to be involved in representing complexity.

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Introduction

The COVID-19 pandemic has influenced numerous points of intersection between built, biotic, social, and health processes. In this discussion, we draw inspiration from conceptual developments in public health that focus on social and environmental 'relations' and the entanglement between biotic/ ecological, social, and health processes (Whitmee et al., 2015; Hinchliffe et al., 2018); as well as integrative approaches to public health (Abrams, 2006; Rashid et al., 2009; Assmuth et al., 2020). By taking the relational approach one factor further to include the built environment; and by broadening disciplinary perspectives to architecture and design, philosophy, and systems biology, our interest is to explore how the built environment regulates multi-process pathways. There has been thorough research about the junctures between built environments, ecological factors, social structures, and health (Hamlin and Sheard, 1998; Frumkin, 2002; Sloane, 2006; Baldwin et al., 2011; Cooper et al., 2011; Strickland, 2014; Schrank and Ekici, 2017; Gruebner et al., 2017; Pinter-Wollman et al., 2018). Our particular aim is to develop a conceptual framework that can embed built environment causal relevance because the representational adequacy of the built environment in scientific models and data practices has been limited, to say the least.

For ease of navigation, section 'Diagnosing representational framework inadequacy: epistemological, ontological, and methodological problems' is directed toward researchers specializing in modeling and methodology in scientific practice; section 'Developing a relation-based representational precedent' is directed toward interdisciplinary and transdisciplinary researchers with skeptical inclinations about integrative public health concepts; and section 'Representing the causal relevance of the built environment', which we take to be the central conceptual contribution of this paper, is directed toward architects, designers, and public health researchers interested in analyzing and visualizing the dynamic roles of the built environment in public health.

Our focus is twofold. First, it is part diagnostic. In section 'Diagnosing representational framework inadequacy: epistemological, ontological, and methodological problems', we draw attention to failures in representational infrastructure and practice, pertaining to complex processes. We present three intertwined problems with scientific representation in COVID-19 data-gathering practices. These problems pertain to missing data, idealized measurement outcomes, and shallow surrogate measures—all of which culminate in misrepresentations of COVID-19 complexities. The overarching general problem can be summarized as follows: to what extent do current measurement and data practices fail to robustly account for the complex *intersections* between built, biotic, social, and health processes? We argue that the first step in solving the presented problems requires the development of new conceptual foundations that set the ground for detailed causal interconnections.

Our second, and larger, focal point is prescriptive. Section 'Developing a relation-based representational precedent' motivates the conceptual need to broaden our representational frameworks by looking at counterintuitive causal relationships in SARS-CoV-2 transmission. For instance, we describe that high-density built environment contexts can maintain low transmission rates and high public health resiliency behaviors. Additionally, we describe how low-density environments can maintain high transmission rates, moderated by factors like built environment connectivity and even social belief systems. We suggest that further parameterization based on contextual factors should be explored in order to adequately represent the junctures between built environment, social, and biotic processes. In our discussion of the ontology of relationality, we argue why the representation of nuanced causal relations within dynamic contexts is paramount for accurate representation (section 'Why focus on relations in COVID-19 contexts?'); and we make a forthright point about difficulties and pitfalls of relation-based integrative public health concepts (section 'Relation-based integrative concepts: warnings and developments').

In section 'Representing the causal relevance of the built environment', we synthesize concepts from different disciplines in order to address how the built environment, centrally, figures into the intersections between biotic, social, and health processes. In section 'Relationality and the built environment: built contexts and nudges' and 'Relationality and the built environment: contexts and affordances', we discuss at least three conceptual developments that can be applied to the built environment: 'nudge', 'affordance,' and 'interface'. The purpose of these concepts is to organize the multiple regulating functions of built environment contexts (BC's). We apply the concepts in order to show how BC's can be cohesively analyzed alongside social and biotic variables—in addition to showing how BC's can be visualized side-by-side with other contexts (section 'Relationality and the built environment: visualizing interactions and interfaces'). Our main argument is that the built environment can be represented not only as a single discrete variable (or handful of variables) but also as an *interface* that reorganizes causal relations—concurrently, deregulating factors, while leaving others unaffected. We conclude that to adequately represent the various moderating roles of the built environment, we must acknowledge *who* ought to be involved in the process of representation (section 'Relationality and the built environment: community participation in measurement practice').

Diagnosing representational framework inadequacy: epistemological, ontological, and methodological problems

Throughout the pandemic there have been many failures in representational infrastructure and practice, pertaining to key social and built environment factors. We argue that expanding representational scope to embed process-intersections requires making deliberate conceptual choices about what to selectively represent. Before we can address adequate representation, we must address inadequate representation of complex process-intersections. That is, to schematize useful representational suggestions (section 'Developing a relation-based representational precedent' and 'Representing the causal relevance of the built environment') it is necessary to first focus on broken representational methods and practices. We present three intertwined problems with scientific representation in COVID-19 data-gathering practices. These problems pertain to missing data, idealized measurement outcomes, and shallow surrogate measures—all of which result in the misrepresentation of COVID-19 complexities. Facing these problems requires reassessing the epistemological comprehensiveness of our representations, the methodological robustness of our measurement practices, and finally, how our scientific frameworks inform epistemological and methodological changes. We argue that the resolution of the presented problems is not "more" data (e.g., higher volume and velocity of data) but, rather, the development of new conceptual foundations that set the ground for a detailed causal topography.

Throughout the pandemic there have been limited measurement practices to adequately account for disparities in COVID-19 morbidity and mortality based on structural racism; and there has been limited representational infrastructure to account for the causal roles of inequitable built environments as moderators for morbidity and mortality. We begin with the former issue. In Keyser and Howland (2020), we describe the unmet need to adequately represent connections between various forms of systemic racism, like environmental racism, and pandemic health outcomes (also see: Washington, 2020; Brandt et al., 2020; Kader and Smith, 2021). One representational problem is the *absence of data outcomes* about race, ethnicity, and social determinants of health, which would require methodological modifications in data-gathering (Keyser and Howland, 2020; Howland et al., 2022). Missing data outcomes result in overlooked disparities. For instance, not only has there been missing COVID-19 morbidity and mortality data about Indigenous populations, there is also methodologically correctable missing EHR data about symptoms, underlying health conditions, hospitalizations, ICU admissions, and mortality (Hatcher et al., 2020; Williamson et al., 2020).

It can be argued that synthesizing complex relations between systemic processes and health outcomes is reserved for the level of theory. However, initial methodological failure occurs at the stage of measurement by ignoring representational factors that could serve as the foundation for theory-building (Keyser and Howland, 2020). For instance, meta-data work on COVID-19 health outcomes and population factors from 50 countries document population characteristics such as socioeconomic status (Chaudhry et al., 2020). While socioeconomic status is causally relevant for the evaluation of health-related outcomes, it does not tell the full causal story. We suggest that data should be further partitioned beyond socioeconomic parameters. For instance, there are racial disparities in built environment pollutant exposure even when socioeconomic status is controlled for (Washington, 2020). Reparameterization could be a first step, although an insufficient one, for increasing causal resolution. In other words, the representational problems go deeper and are not resolved by a surface-level parametrization. The reason being that data partitioning merely based on race, ethnicity, and socioeconomic factors still risks using general surrogate measures and skewing causal complexity.

There is an intertwined representational problem about the ontology used within our research programs: the absence of a representational framework that can embed causally relevant built environment processes that promote disproportionate health outcomes. For instance, currently there is limited infrastructure in electronic health records (EHR), used in machine learning models, to account for the causal role of inequitable built environments as moderators of morbidity and mortality (Howland et al., 2022). Built environment factors have seemingly important, but epistemologically opaque, regulating causal roles in our current research perspectives. Significant findings based on data from 3000 US counties predict that a 1 $\mu g/m^3$ increase in chronic $PM_{2.5}$ exposure is associated with a 9% (95% CI 6–12%) increase in COVID-19 mortality (Coker et al., 2020). But such data fails to account for disproportionate pollution effects. For example, in a joint workshop report of ERS, ISEE, HEI and WHO, air pollution and its relation to COVID-19 severity is discussed but the only reference to social determinants of health is that they "…are clearly visible around the world" (Andersen et al., 2021, p. 4). Adequate representation of specific causal roles at the intersection between the built environment and social determinants of health is missing. Brandt et al. (2020) hypothesize disparate exposure to air pollution as a causal factor that contributes to the disproportionate impact of COVID-19 on Black and Latinx populations. The hypothesized moderating role of built environment pollution on health disparities is significant (Terrell and James, 2020; Dey and Dominici, 2021); but there is still a need for conceptual and methodological infrastructures to account for the nuanced causal roles of the built environment. Brandt et al. (2020) present the methodological need to factor in new types of measures and models about 'accumulated lifetime exposure' to explain why the temporary decrease of $PM_{2.5}$ will not alleviate health outcome disparities. A set of ontological, epistemic, and methodological questions emerge: How do we represent the specific *regulatory roles of the built environment*; How do we operationalize those regulatory roles; and How do we create new methodologies to address those roles?

An argument that data practices and theory-development will "eventually" lead to causal resolution is not sufficient because initial representational steps lack fine-grained details about causally relevant built environment factors. For example, current studies that link long-term exposure of $PM_{2.5}$, PM_{10}, NO_2, and CO to decreased COVID-19 outcomes (Pansini and Fornacca, 2020; Fattorini and Regoli, 2020; and Wu et al., 2020) do not document race and ethnicity, let alone details like accumulated lifetime exposure or local variations in built environments and pollution. In other meta analyses that assess ambient air pollution and COVID-19 (Zang et al., 2022; Marquès and Domingo, 2022), multifactorial risks, race, ethnicity and social determinants of health are severely lacking or fully missing. Changes in measurement methodology and data-partitioning are necessary to understand the causal roles at the *intersections* between social and built environment factors. To clarify, this is a problem with *selective representation* in our data and modeling practices (Keyser and Howland, 2020): certain variables are explored while others are ignored; and key process-intersections are fully unaccounted for.

A humanities lens offers some perspective about selective representation in science. According to 'perspectivism' in the philosophy of science literature, measurement, experimentation, and modeling all produce limited representations of real systems; and those representations are accurate to aspects and degrees (Giere, 2006; van Fraassen, 2008; Massimi and McCoy, 2020; Keyser and Howland, 2020). For instance, a given representation can capture key properties of a system, while missing or idealizing other properties. Even if current COVID-19 research is pushing for the evaluation of new causal factors (e.g., pollution particle types) there is still a need to evaluate other ecological, built, and social factors. We take the view that a given real system is relationally complex. However, by creating robust measurement and modeling perspectives, we can aim to adequately represent important features and relations of a given system. The 'perspectivism' conceptual framework can be boiled down to a precise visual. Imagine a set of complex intersecting processes and multiple ways of selectively representing those processes (see Fig. 1). Our initial step in the diagnoses of scientific practice in COVID-19 is to understand how we are failing to expand perspectival/representational scope to intersections that involve built and social processes. Notice that although Fig. 1 is a general schematic of representational scope, there are a number of precise points of reference. First, causal factors can be represented as intertwined processes instead of as simple nodes. It is important to emphasize that a given built environment should not be reduced to a single factor; rather, it should be investigated as an evolving process (in section 'Developing a relation-based representational precedent', we discuss that reductionism has been an issue when it comes to representing the built environment.) Second, we draw attention to the importance of investigating process-intersections for the purpose of understanding compounded and emergent effects. For instance, built and social processes can concurrently determine social activity, relevant to public health outcomes. Chang et al. (2021) highlight the extent to which race, ethnicity, and socioeconomic status limit the set of mobility pathways within built environment contexts, creating incongruent risks in COVID-19 morbidity. Failures in widening representational scope over process-intersections may also indicate failures in interdisciplinary and transdisciplinary scientific collaboration. After all, the synthesis of built, biotic, and social factors within a given measurement practice requires multiple

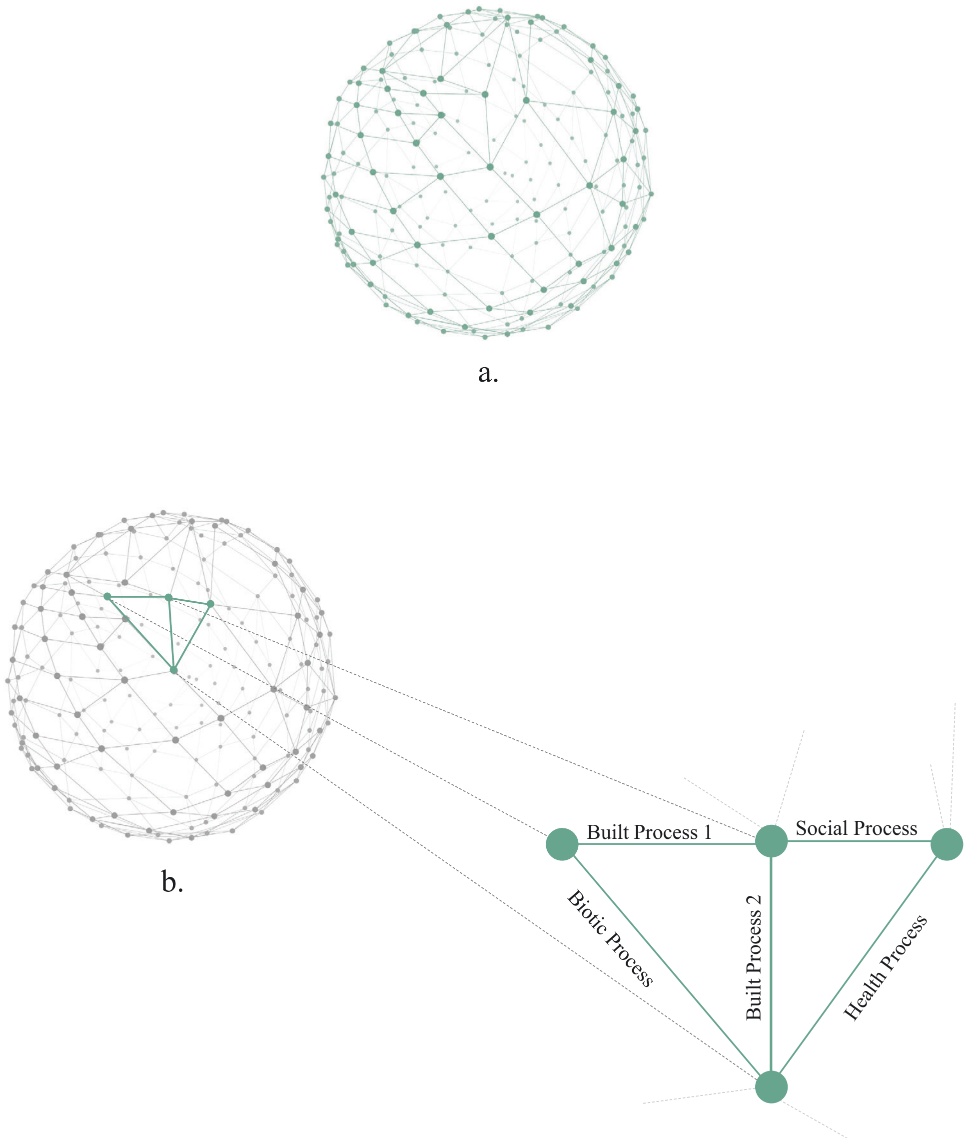

Fig. 1 Representational scope. This is a general schematic of representational scope, where a given system is depicted as intersecting processes (**a**); and scientific perspectives can be used to selectively represent aspects and degrees of that system (**b**). Causal factors are represented as intertwined processes with a focus on process-intersections (**b**). For instance, a given built environment process and a given social process can concurrently determine social activity relevant to some biotic process.

disciplines—an issue that we will return to in section 'Developing a relation-based representational precedent'.

So far, we have discussed representational failures in data-gathering and partitioning. But there are similar issues with selective representation, pertaining to predictive algorithms in COVID-19 contexts, where representational frameworks do not account for causally relevant variables. Selective representation of public health causal factors is sometimes applauded due to effective general prediction. In Howland et al. (2022), we make the point that predictive success in machine learning does not translate to representational adequacy; and we suggest new ways of incorporating information about social determinants of health and inequitable built environments into machine learning practice. In electronic health record (EHR) settings, it may be too much to expect someone to answer detailed questions about lifetime pollution exposure and other relevant built environment factors. But this need not deter us from incorporating built environment variables into EHR data practices. GIS data about built environment pollution is readily available and could be integrated into EHR. Reliable methods for GIS-EHR integration have been explored (Laranjo et al., 2016; Zimeras et al., 2009). But to apply those methods to relevant COVID-19 parameters, a representational precedent has to serve as an adequate guide.

It is worth noting that other researchers have rigorously pursued 'small data' to investigate fine-grained causal relations in built environments—e.g., by investigating how built environment airflow processes moderate transmission (Lu et al., 2020; Kwon et al., 2020). Kwon et al. (2020) have integrated viral genome data from local hospitals, GIS data, CCT footage, cross-referenced travel data, and recreated built environment conditions to trace how airflow pathways and seating arrangements can spread SARS-CoV-2 particles ~21 feet and infect individuals in around five minutes exposure. While there is much to improve, methodologically—including stricter evaluation of genome matching and elimination of other social contact—such scientific work is fascinating because of its integration of methods (clinical, GIS, and built environment measures) and evaluation of multiple variables and scales—with the built environment serving a crucial moderating role.

Beyond selective representation in epidemiological and EHR data, the same problem exists in computational models that attempt to predict the behavioral dynamics of social contact. Cutting-edge computational research presents a model of adaptive, optimal control of social contact rate (Arthur et al., 2021). The model focuses on variables like economic and personal health costs, and crucially, information time delay. 'Optimal contact rate' is modeled as a utility function, parameterized by perceived risks and benefits of social contact. This adaptive social contact model usefully predicts the importance of early lockdown interventions, in addition to other interesting conclusions about oscillatory dynamics—e.g., dynamic regimes occur more often when there is a time delay (Arthur et al., 2021). But there are a number of representational idealizations. Some are transparently stated. The authors admit that the model homogenizes individual responses to government policy. But there is a deeper representational issue. As we analyze in section 'Developing a relation-based representational precedent', socio-behavioral responses are associated with moral and social belief systems that are inextricably embedded within *contexts*. The authors state that, "Geographic and/or cultural variation in our parameter ['optimal contact rate'] (and concomitant variation in the delay Δ) are likely to affect how epidemic dynamics are affected by such trade-offs" (Arthur et al., 2021). We suggest that rather than taking the long view that geographic, cultural, and other variations will likely be "filled in" with later iterations of the model, it is crucial to understand *how* such parameters can be represented as differentially moderating the optimal contact rate in diverse contexts. For instance, applied empirical research differs with the Arthur et al. (2021) model implications, precisely for context-specific reasons—e.g., studies that focus on race, ethnicity, culture, and incongruent risks, moderated by mobility pathways, provide more nuanced early mobility restriction suggestions (Chang et al., 2021). Additionally, as we will see in section 'Representing the causal relevance of the built environment', there are counter-intuitive causal relations between the earliness of lockdown, increased reactance, and reversal of the success of some types of 'nudge' interventions. The causal connections relevant for evaluating COVID-19 social contact rates are quite sensitive and necessitate a detailed analysis of social, built environment, and biotic factors—with a focus on how contexts shape relationships between factors. Adequately representing contextual variations requires scientific work that extends beyond merely filling in new variable values within the existing model. It requires a reconstruction of the model with a new set of variables that adequately reflect changing multivariable landscapes (see section 'Representing the causal relevance of the built environment').

Combining the aforementioned problems—failures of selective representation in epidemiological data and EHR, as well as failure to reflect relevant upstream causal connections—we present a general issue for scientific practices in COVID-19 contexts. The preceding problems stem from the *reliance on surrogate measures* within our measurement and data practices. For instance, when implementing predictive models that use binary questions about race, fully missing parameters on built environment pollution exposure, and comparatively inadequate biomarkers that impede deeper investigation into structural and social determinants of health (Howland et al., 2022), we cannot expect to improve causal resolution of *multifactorial relationships*.

Generally, a surrogate measure/marker can serve as a substitute for a clinically meaningful endpoint (De Gruttola et al., 2001), although in this discussion we characterize 'surrogate measures' more generally to describe substitute or inferential measures. A representational and methodological ideal is a surrogate measure that provides reliable information, regarding processes that cannot be investigated directly. For instance, pragmatically we cannot track each individual case of transmission to map out causally relevant factors, so surrogate measures are needed for ease of general prediction and explanation. Likewise, high-risk vs. low-risk COVID-19 prediction can become causally cumbersome, so risk prediction models, like the one developed by Garibaldi et al. (2021), provide a small set of surrogate parameters to make quick predictions—e.g., white blood cell count, absolute lymphocyte count, and respiratory rate—in addition to a set of questions about symptoms and risk factor parameters (Howland et al., 2022).

The ideal scenario for a valid surrogate measure is that multifactorial processes are causally tied to some surrogate measure, which is strong in both specificity and sensitivity (see Fig. 2. S0).[1] This ideal scenario is rarely met in biological surrogate measures. But we suggest that a *combination of biological, social, and built factors* makes surrogate measure use even more methodologically complicated. We propose that there are a number of parallel surrogate measure problems, similar to ones from biological surrogate measures (Fleming and Powers, 2012; Keyser and Sarry, 2020), which are relevant for modifying COVID-19 scientific practices. Surrogate measures pose at least 3 abstract problems (see Fig. 2). Each problem pertains to the adequate representation of multifactorial upstream causes. We argue that surrogate measures alone do not provide the topographical causal story about relations; and hastily acquired surrogate measures can impede causal clarity and misrepresent relevant upstream causes —especially about social and built environment factors.

Ignored upstream causes. As Keyser and Sarry (2020) outline, a precursor factor, context, or event can create branching parallel causal pathways, such that the surrogate measure does not tie into the causal pathway of the relevant health outcome (Fig. 2. S1). This would be akin to using a biomarker measure to differentiate high-risk vs. low-risk COVID-19 infection, while ignoring other biomarker pathways with specificity and sensitivity, relevant to the disease outcome. For instance, we have argued elsewhere (Howland et al., 2022) that IL-8 has been missing as a key biomarker in recent machine learning models, even though it shows promising results for predicting mild vs. severe disease prognosis, especially in the context of multifactorial interleukin evaluation (Li et al., 2021). One representational concern is that by focusing on limited biomarkers a different pathway, consisting of relevant *upstream cascading factors* ($f_1, f_2, \ldots f_n$), may be fully ignored (Fig. 2. S1). The same problem can be found in surrogate measures that lie only within one of many parallel causal pathways in multifactorial processes that are relevant to some health outcome (Fig. 2. S2).

We propose that the need to represent upstream complexity extends beyond a given biomarker's predictive usefulness. Adequately investigating upstream causes opens avenues to representing the roles of social determinants of health. For instance, analytical methods suggest that multiple molecular mechanisms are overexpressed due to social determinants of health (Gaye et al., 2017). The overexpression of a number of genes in IL-8 signaling pathways—e.g., CXCR1, CXCR2, GNG10, and LIMK2—is robustly associated with a combination of social stressors (Gaye et al., 2017). Important for our later discussion of ontology, Gaye et al. (2017) describe the significance of evaluating *context-specific* molecular effects—e.g., in inequitable "social environments", constituted by a number of "psycho-social" factors (p. 11). Note here that a given set of social determinants can be represented as moderating the molecular mechanisms responsible for a given pro-inflammatory response. The relevant representational pathway can be characterized as upstream causal factors that begin with social and structural determinants (F_1), move to epigenetic processes (F_2), and culminate in pro-

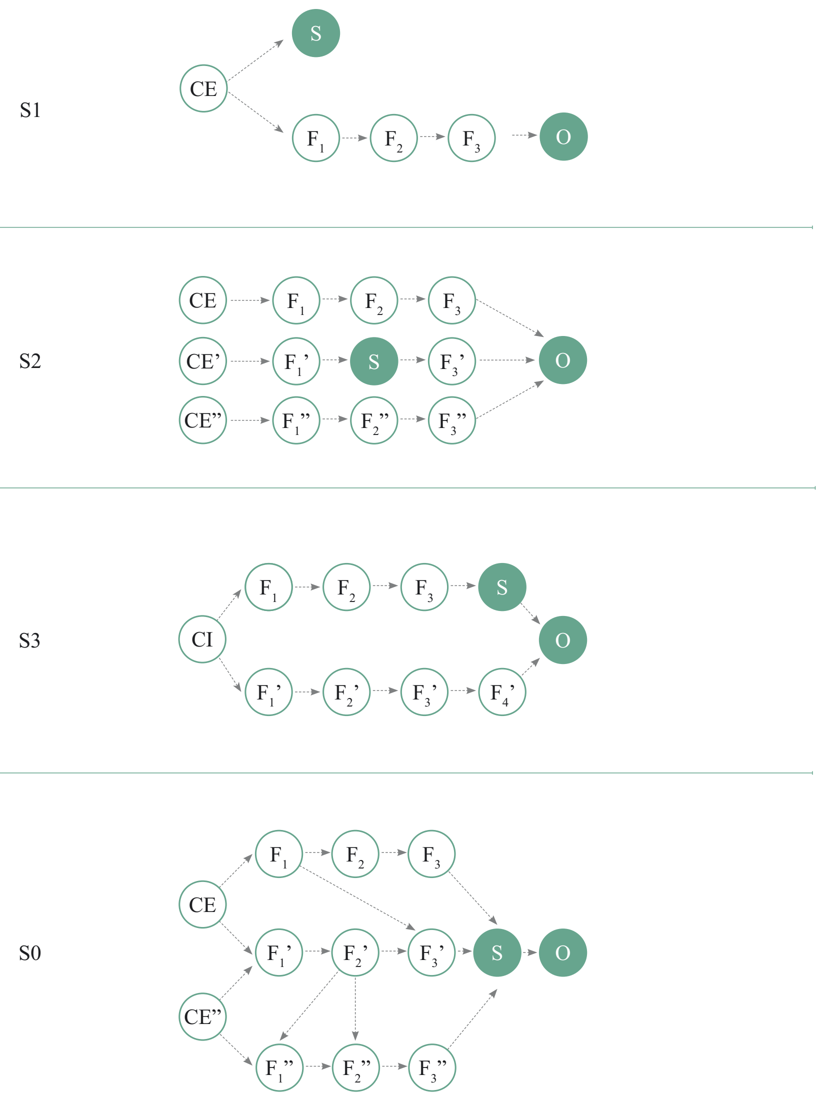

Fig. 2 Surrogate measures. The various forms of surrogate measures. CE (or, "E" for short): causal event; S: surrogate measure; F: causal factor; O: measurement outcome; CI: causal intervention. These representations are adapted from the account presented by Fleming and Powers (2012) and detailed in Keyser and Sarry (2020). Beginning with S0, the ideal scenario for a valid surrogate measure is that multifactorial processes are causally tied to some surrogate measure, which is strong in both specificity and sensitivity. In S1, branching parallel causal pathways are represented such that the surrogate measure does not tie into the causal pathway of the relevant health outcome. In S2, surrogate measures lie only within one of many parallel causal pathways in multifactorial processes that are relevant to some health outcome. In S3, a surrogate measure can be modified by some intervention, event, or context that has direct and/or indirect off-target effects on the health outcome of interest. This scenario is difficult to causally disentangle because the surrogate measure is modified by the intervention, concurrently, as that intervention modifies other off target effects.

inflammatory IL-8 signaling (S) and, subsequently, some relevant health outcome (O). Investigating only one biomarker (e.g., IL-6) can risk missing upstream complexity (Fig. 2. S1) (Howland et al., 2022). So, while IL-8 can offer predictive utility as a quick EHR measure, it can also serve as an 'information lever' for the deeper epidemiological causal story about how social determinants of health are promoting health disparities (Howland et al., 2022). Notice that for the sake of simplicity, this example includes linear pathways only and does not address the difficulty of complex social and built process analysis, which we address in section 'Representing the causal relevance of the built environment'. The upshot to more nuanced causal representation is that the junctions between built environments and social determinants of health can be adequately tracked.

Multifactorial relationships stemming from built environments. As Keyser and Sarry (2020) detail, a surrogate measure can be modified by some intervention, event, or context that has direct and/or indirect off-target effects on the health outcome of interest (Fig. 2. S3). This type of scenario is difficult to disentangle, causally, because the surrogate measure is modified by a given intervention at the same time as the intervention modifies other off-target effects. As we expand in section 'Representing the causal relevance of the built environment', even simple built environment changes/interventions can create branching causal pathways, which are difficult to represent. For instance, public park closure can prevent virus transmission within the population; but it can also inhibit resilience-promoting community movement behavior, while concurrently moderating molecular mechanisms relevant to lung inflammation.

Although the configuration in Fig. 2. S3 provides a useful starting step for synthesizing built, social, and health factors, one representational problem persists: the oversimplification of built environment factors. It is important to note that a diagrammatic structure like S3 fails to represent how built-to-social relations change within a given *context*. Filling in parallel built factors (f_1 and f_1') is just the initial step in visualizing how a given built environment regulates multiple factors that can, subsequently, produce amplified effects on a given health outcome; but the representational picture is still quite limited.

In summary, surrogate measures alone do not provide a topographical causal story about relations between built, social, biotic and health processes. Additionally, hastily acquired surrogate measures can impede causal clarity. The purpose of discussing surrogate measure problems is to illustrate just how much representational work lies ahead, if we aim to go beyond shallow and limited measures in our data, EHR, and modeling practices. One might argue that finding valid surrogate measures and clarifying complex sociobiological mechanisms are separate scientific activities. But we think that these activities can inform each other. That is, by providing an adequate representational infrastructure and filling in causally relevant intersections, we can generate more robust surrogate measures, which can, in turn, dial up causal resolution in our models and measurement practices. Furthermore, in the next section we argue that solving these representational problems requires perspectival input from independent disciplines in order to piece together a representationally robust picture. We suggest that epistemic opacity goes hand-in-hand with a lack of infrastructure in interdisciplinary and transdisciplinary frameworks for the investigation of complex, intertwined processes.

So far, we have presented a general problem: To what extent do current measurement and data practices fail to robustly account for the complex intersections between built, biotic, social, and health processes? Taking a fine-grained view, there are a number of interrelated problems:

Measurement outcome problem. There is an *absence of data outcomes* about race, ethnicity, and social determinants of health, all of which would require a methodological modification in data-gathering and/or analysis. While this may seem easily correctable, it points to two deeper problems.

Representational framework problem. There is an absence of a representational framework that can embed causally relevant *processes*, responsible for disproportionate health outcomes. Related to the aforementioned problem, an absence of data outcomes can occur from a lack of representational infrastructure to account for the causal roles of inequitable built environments on health outcomes. Built environment factors can operate at many scales; and while some built environment moderating roles should be obvious, they are currently not being integrated into interdisciplinary and transdisciplinary research programs. As we will expand in sections 'Developing a relation-based representational precedent' and 'Representing the causal relevance of the built environment', built environment contexts, consisting of multiple variables, can *moderate* environmental and biotic factors, behavioral nudges, and norm changes in populations.

Surrogate measure problem. Surrogate measures alone do not provide the topographical causal story about relations; and hastily acquired surrogate measures can impede causal clarity and misrepresent relevant upstream causes.

The larger projects ahead of scientific communities include adequately representing multi-process intersections and incorporating new representational frameworks into scientific practices. But small steps can be taken to solve the Outcome, Representational Framework, and Surrogate Measure Problems. Our contribution to solving these problems is conceptual. We describe a representational precedent that focuses on 'relations' (section 'Developing a relation-based representational precedent'), and we clarify how to represent the unacknowledged moderating roles of the built environment (section 'Representing the causal relevance of the built environment').

Developing a relation-based representational precedent

Confronting the aforementioned representational problems requires building a conceptual precedent that can *embed* new ways of representing complex processes. In section 'Representing the causal relevance of the built environment', we discuss how the various roles of the built environment can centrally figure in the development of new modeling and methodological approaches. But first, it is important to expand the motivations for a conceptual precedent that focuses on an ontology of *relationality*: Why is the representation of nuanced causal relations important in COVID-19 contexts (section 'Why focus on relations in COVID-19 contexts?'); and what are some difficulties and pitfalls of relation-based integrative public health concepts (section 'Relation-based integrative concepts: warnings and developments)'? These focal points are key for understanding the challenges of conceptual cartography ahead of us, if we hope to challenge the aforementioned representational problems.

Why focus on relations in COVID-19 contexts? It might appear that representing nuanced causal interconnections may not constitute an effective scientific approach for quick prediction and explanation. Why not focus scientific efforts on pinpointing the *most critical* variables for SARS-CoV-2 transmission? For instance, population density is a key determinant of transmission and replication, so while interconnections between multiple factors might be relevant for piecing together a larger explanatory picture, such an approach is not necessary for proactive interventions. However, a deeper investigation into relationships reveals counterintuitive, critical variables at the *intersection between the social, biotic, and built*.

Unusual relationships exist between high population density and low doubling times of virus spread. It turns out that virus transmission rates in dense populations are significantly associated with moral and social belief systems. First, high self-reported belief in freedom of assembly, association, and agency are correlated with increased COVID-19 transmission rates (Kapitány-Fövény and Sulyok, 2020). In fact, internationally-gathered data supports that individualistic belief cluster variables (e.g., assembly, association, and agency) are more accurate predictors of transmission rates than GDP per capita, government effectiveness, preventative interventions, or quality of/access to healthcare (Kapitány-Fövény and Sulyok, 2020) (we return to individualism in section 'Representing the causal relevance of the built environment', where we discuss its obstacles for planning effective nudges). Additionally, even in *low* population density and *high* per capita GDP, civic and social participation, government effectiveness, preventative interventions, freedom of assembly and association, personal and family relationships, there is a significant increase in COVID-19 transmission rates (Kapitány-Fövény and Sulyok, 2020). Furthermore, placing high value on doing something good for society and behaving properly do *not* decrease COVID-19 transmission; likewise, high transmission rates exist even in contexts where belief systems focus heavily on personal, family, and social network relationships (Kapitány-Fövény and Sulyok, 2020). This is rather puzzling because, intuitively, it seems that consequentialist, deontological, virtue, social, care, and public good belief foundations should have a significant effect on transmission rate. Instead, societies that are "compliant" to both individuals and their governments showed the highest doubling times (i.e., lower virus transmission) *even in* *the context of increased population density* (Kapitány-Fövény and Sulyok, 2020).

To frame this data, using comparative 'robustness analysis' (Keyser and Sarry, 2020), even when countries and environmental contexts vary, beliefs about doing something for the good of society, social group, and family, in addition to beliefs about proper behavior, are not sufficient for COVID-19 transmission decrease. Additionally, government conformity alone is not effective for transmission decrease. Moreover, comparatively *lower* scores on doing something for the good of society and behaving properly do not result in increased transmission rates. Interestingly, much of the Kapitány-Fövény and Sulyok (2020) data parallels independent pre-COVID data on the effectiveness, or lack thereof, of regulatory behavioral 'nudges' in different countries, which will be discussed in section 'Representing the causal relevance of the built environment'. This is just one small-but-crucial focal point at the intersection between moral and social beliefs and biotic processes. If we scientifically represent the pandemic context as being regulated mostly by density and movement, we will miss key and counterintuitive causal relations, linking belief systems to transmission rates. This is also why a conceptual precedent has to be set for *representing the varying 'contexts' of the pandemic*. That is, it is not the case that contexts are homogenous with respect to causal variables—even if they appear to be similar. We turn to this point.

Behaviors are shaped by environmental and built contexts. Kapitány-Fövény and Sulyok (2020) make a broad, speculative point about the connections between belief systems, social relationships, and socio-environmental contexts. But we argue that one can see direct examples of behavior within specific contexts by analyzing features of the built environment. Quite obviously, built environment contexts are causally relevant to density and movement. Large metropolitan areas have had higher infection and death dates compared to low-density communities (Florida, 2020; Rocklöv and Sjödin, 2020). This is due to higher connections and social interactions (Hamidi et al., 2020). However, Hamidi et al. (2020) found that after controlling for metropolitan population, county density is unrelated to confirmed SARS-CoV-2 infection rates and is inversely related to confirmed virus death rates—putting into question city planning focused on sprawl for public health purposes, as well as the predictive and explanatory relevance of 'density' over more adequate built environment variables like 'connectivity'. In this case, attention is drawn to community movement and interaction, *moderated* by built environment variables beyond density.

Noteworthy for exploring new variables in the built environment, higher COVID-19 morbidity and mortality rates result in higher outdoor activity restriction (de Lannoy et al., 2020). Clearly, the built environment can constitute mediating and moderating structures for transmission. But it can also serve as a substrate for resilience-building behaviors. The representational focus on the latter has received minimal attention. The built environment can promote "community resilience" through healthy movement behaviors (Mitra et al., 2020). Specifically, even though dwelling density is usually associated with decreased outdoor activity, access to parks within 1 km shows promising increased outdoor activity that promotes healthy movement behaviors in COVID-19 (Mitra et al., 2020). Here, the representational implication is to focus on how relevant built environment contexts (RBEC's or, BC's) modify public health outcomes, transmission being just one relevant public health outcome.

We make two points about representational infrastructure limitations. First, there has been a limited focus on the *regulatory role* of the built environment on social and biotic processes—especially the health-promoting roles of built environments. Second, RBEC evaluation is often subject to simplification and misrepresentation. For instance, take the already-limited set of RBEC's applicable to density and movement. Hamidi et al. (2020) discuss parameterization based on "compactness indices", which are the opposite of sprawl indices and consist of an amalgam of variables, measuring four dimensions of the built environment—e.g., density, mixed use, activity centering, and street connectivity. Unaccountably, often only one of these variables is used in a given study (Hamidi et al., 2020). Such choices constitute epistemological and methodological limitations that prevents deeper analysis of built environment and health outcome relations. For instance, in the aforementioned RBEC studies on movement, it is assumed that a given RBEC, homogenously, affects population movement—whether county travel or healthy movement behavior. However, we have seen that built contexts can be modified by environmental racism, which can thwart resilience-promoting interventions. During the first wave of pandemic lockdown, it became apparent that public park access is not equitable for a number of reasons: lack of parks in close proximity to Black and Latinx populations; park entry fees; and various forms of racial discrimination (Burrowes, 2020). We suggest that built environment representations must focus on detailed causal relations within *contexts*. Well-rounded contextual representations could promote more nuanced interventions that are directed toward equitable park access—e.g., interventions proposed by the 2019 Urban Institute report, "Investing in Equitable Urban Park Systems" (Eldridge et al., 2019).

It is important to avoid conceptual vagueness about 'context'. There have been thorough conceptual developments in areas of research such as, Urban Geography, Sociology, and Environmental Cognition. Gerson and Gerson's (1976) account broadens RBEC scope beyond limited variables like compactness indices. A given 'place', consisting of physical processes, modifies the interactions, conduct, and perspectives of its individual and collective occupants (Gerson and Gerson, 1976). Furthermore, there are feedback loops between the physical components of a place and the agents that occupy it, such that 'mutual adjustment' and, what we call, *co-modification* occurs: Places modify agents by shaping value systems, pace and type of interaction, as well as qualitative perspectives; and those agents, in turn, modify the built and natural features of a place (Gerson and Gerson, 1976). Additionally, we can add that different contexts—composed of physical, value-laden, temporal, and existential interactions—produce *emergent* properties. Gerson and Gerson's (1976) 'place perspectives' can be utilized to explain non-homogenous causal relevance within a place. Even within the same location, one person may have access to public health-promoting pathways, while another may occupy a number of interaction-dependent contexts, where all roads are blocked (e.g., adequate healthcare, equitable resource access, and resilience-promoting movement). We explore a multitude of relational concepts in section 'Representing the causal relevance of the built environment'. For now, the benefit of such a conceptual precedent—one that focuses on causal feedback loops within places—is that it precisely organizes existing complex relationships instead of making homogenizing causal idealizations.

To summarize, counterintuitive causal connections are informative even when critical COVID-19 variables like density appear as the obvious causal culprit. High-density contexts can maintain low transmission rates and high public health resiliency behaviors. We suggest that parameterization based on contextual factors should be explored, like the *intersections* between belief systems and biotic processes or the intersections between built environment contexts and biotic processes. Essentially, a conceptual infrastructure should be sought out to provide adequate characterizations of 'relation' and 'context'.

Relation-based integrative concepts: warnings and developments. The general purpose of our discussion is to ground the importance of developing relational perspectives on complex entangled systems. But first, it is necessary to make a forthright point about using catching words—e.g., 'relational', 'integrative', and 'transdisciplinary'—in order to promote conceptual clarity. When specified, such concepts can be methodologically useful; otherwise, they may promote disciplinary silos. Additionally, our concern, in line with section 'Diagnosing representational framework inadequacy: epistemological, ontological, and methodological problems', is that by getting the ontology wrong the epistemology and methodology suffer.

Definitions of 'transdisciplinarity' offer many conceptual pathways. For instance, there is a sharp distinction between transdisciplinary focus that is directed toward abstract epistemological holism, consisting of "unity of knowledge", compared to pragmatic participatory problem-solving approaches (Scholz and Steiner, 2015). The latter offers *methodological heterogeneity*—i.e., different viewpoints, experiences, and skills—in addition to *mutual learning* between scientists and participants (Scholz and Steiner, 2015). Others have developed similar methodological perspectives, where transdisciplinarity focuses on "bottom-up mutualization of methodologies and theories" (Rigolot, 2020). The upside of the participatory problem-solving approach is that two dimensions to 'transdisciplinarity' are emphasized: a focus on synthesizing multi-methods and an interest in coordinating scientists and other participants (e.g., stakeholders and, hopefully, community members).

The downside is that vague conceptions of 'transdisciplinarity' have led to methodological problems—such as, the fragmentation and reinvention of methods. As a result, new integrative concepts have emerged to synthesize disciplinary and stakeholder knowledge, and to develop new approaches for policy changes (Bammer, 2017). Views like 'post-normal sustainability technologies' (PNSTs) (Frame and Brown, 2008) and 'integration and implementation sciences' (i2S) attempt to fulfill a similar role to 'transdisciplinarity', e.g., by positing an iterative problem-solving process with integration and implementation at every stage. But new and multiplying concepts often miss the same key problems as their predecessors. One issue is about specifying methodology —i.e., how does bottom-up mutualization work relative to a particular problem? A second issue is that many transdisciplinary approaches refer to stakeholders and public parties beyond academia (Scholz and Steiner, 2015); but larger integrative *activities* end up solely in scientific communities (Bammer et al., 2020). That is, in these integrative approaches there are often vague suggestions for societal dimensions and culturally inclusive frameworks. If specified, both could promote conceptual and practical developments. But there is no specification for *how* applied activities work. Specific methodological suggestions with clear aims for public participation are particularly important in COVID-19 contexts, if our temporal goal is to intervene quickly and flexibly. However, vagueness in applied transdisciplinary activities can be a function of vagueness in conceptual foundations behind methodology. As we discussed in section 'Diagnosing representational framework inadequacy: epistemological, ontological, and methodological problems', specifying methodology requires fine-tuning conceptual foundations, for instance, by detailing how to parameterize intersecting systems in our measurement and modeling practices.

Ideally, integrative concepts of health can transform epistemological and methodological realms to set the ground for future transdisciplinary practice (Allen-Scott et al., 2015; Schelling and Zinsstag, 2015). The benefit of such concepts is that a fully developed view of 'transdisciplinarity' is not necessary in order to achieve important epistemological and methodological *approaches*. However, Assmuth et al. (2020) point to a number of problems with integrative approaches in public health. Integrative health concepts and advances create disciplinary siloes—with expansion being dependent on funding privileges (Manlove et al., 2016; Assmuth et al., 2020). Such concepts also implicitly and explicitly contain both anthropocentric and Eurocentric frameworks, resulting in dominance of concepts, approaches, narratives, and policies (Assmuth et al., 2020). *Who* shapes the integrative approach becomes paramount to the practice and method (a point that we come back to in section 'Relationality and the built environment: community participation in measurement practice'). Additionally, integrative health concepts lack the fine grain to analyze societal dimensions and natural systems (Lapinski et al., 2015). Finally, they have limited socioeconomic representation; and, for the most part, lack detail about contexts and processes (Assmuth et al., 2020). Particularly important for our discussion in section 'Representing the causal relevance of the built environment' is the lack of integrative concepts that focus on *socio-ecological processes and contexts*. However, getting a fully developed integrative concept that is applicable to changing pandemic contexts might be a *multi-stage* pursuit—such that, from the research-and-development vantage point, we have not even left the surveying stage. Even not-so-new interdisciplinary fields like ethnobiology—focusing on the relationships between humans, cultures, and the biophysical environment—are going back to the drawing board to figure out where the discipline should go, post-pandemic. Interestingly, the majority suggestion is to explore impacts on local communities and researcher-to-community *relationships* (Vandebroek et al., 2020). Fret not, even at the surveying stage there is a clear conceptual goal, arising from all of the integrative concept discrepancies and shortcomings.

We find the transparent academic call for reevaluation of relationships, namely the *type* and *direction* of relationships, particularly important as a starting step toward conceptual clarity. Assmuth et al. (2020) argue that many integrative concepts misrepresent relationships: concepts like 'One Health' (Schrank and Ekici, 2017; Gibbs, 2014; Zinsstag et al., 2015; Woods et al., 2018), EcoHealth (Wilcox, 2004), 'ecosystem health' (Schaeffer and Novak, 1988), and 'planetary health' (Cannon, 2002; Johnston et al., 2005) have a notable limitation of anthropocentrism, as well as a limited focus on socio-ecological interconnections. For instance, in the literature on One Health and ecosystem/environmental health, the environment is often represented as an 'external influence' (Assmuth et al., 2020). Similarly, anthropocentrism often makes its way into sustainable process-views of the built environment. 'Green design' (Fuller, 1969; Papanek, 1985; Burrall, 1991; Mackenzie, 1997), 'eco-design' (Tischner and Charter, 2001; Boks and McAloone, 2009; Pigosso et al., 2015), and 'cradle-to-cradle design' (C2C) (Braungart et al., 2007; McDonough and Braungart, 2002), offer relation-focused perspectives between built, ecological, and social environments—but with limited perspectives on complex ecological and social processes. In this case, the implicit representational problem constitutes treating ecological processes as 'external influences' and ignoring intricate socio-ecological relationships. We suggest that both biotic and social-sustainability conceptual infrastructures can benefit from the development of a more robust process ontology, focused on relations.

Our motivation for this section is to be upfront about gaps in integrative concept developments. We are still in the early stages of incremental concept- and method-building. Our overall contribution to the construction process is to unpack 'relationality'—specifically, how it pertains to the built environment (sections 'Relationality and the built environment: built contexts and nudges'; 'Relationality and the built environment: contexts and affordances'; 'Relationality and the built environment: visualizing interactions and interfaces'). However, it is also to propose a specific public-centered methodology for parameterizing the built environment (section 'Relationality and the built environment: community participation in measurement practice'). We are not proposing a new top-down integrative concept. Rather, we take a bottom-up approach of tracing fine-grained built environment regulating functions. We draw conceptual inspiration from Hinchliffe et al.'s (2018) discussion of 'healthy publics'. According to Hinchliffe et al. (2018), "Healthy publics are collectives that take seriously the social and environmental relations that make health and well-being possible. These are dynamic collectives, composed of people, material processes, and ideas that can provide conditions for health and well-being" (Hinchliffe et al. 2018, p. 8). Particularly important for our discussion, Hinchliffe et al. (2018) emphasize the role of *relations* in their account of healthy publics: "These [relations] may range, as we have suggested, from the social relations that characterize a community, to the ecological and material relations that make health possible to the systemic inequalities, institutional and other structural determinants that shape how opportunities for health and well-being are unevenly distributed (Dutta, 2010)" (Hinchliffe et al., 2018, p. 6). The relationships between culture, social structure, and ecological settings produce emergent properties, which can shape access, opportunity, and outcomes in health (Hinchliffe et al., 2018). We believe that this makes the adequate representation of causal intersections all the more important for understanding the dynamics of health processes in complicated biotic and social environments. For instance, food insecurity, caused by inequitable social pathways, can be exacerbated by environmental contexts, resulting in reduced health outcomes, even in the presence of proper pharmaceutical interventions (Whitmee et al., 2015, p. 1986).[2] Upstream intervention within both social and environmental contexts becomes necessary before downstream pharmaceutical intervention can be effective. Understanding the multi-scale topography of biotic and social environments can guide effective health intervention planning.

By taking the relational approach one factor further to include the built environment; and by broadening disciplinary perspectives to architecture and design, philosophy, and systems biology, our interest is to explore how the built environment regulates multi-process pathways. There has been thorough research about the connections between built environments, ecological factors, social structures, and health (Hamlin and Sheard, 1998; Frumkin et al., 2002; Sloane, 2006; Baldwin et al., 2011; Cooper et al., 2011; Strickland, 2014; Schrank and Ekici, 2017; Gruebner et al., 2017; Pinter-Wollman et al., 2018). Our particular interest is a conceptual framework that can embed built environment causal relevance. Specifically, representational adequacy of the built environment has been limited, to say the least. As Clifton and Perez (2015) note:

> The built environment has been represented in empirical analysis as discrete, disaggregate variables representing individual elements and as composite measures of the environment, such as indices or factors (e.g., Galster et al., 2001; Walk Score). The former offers insight for planners and designers seeking to create specific built environment policies, such as residential densities. But these may not adequately capture the ways that individuals perceive and react to their environments. (454)

Not only are there limitations in how we represent the various causal roles of the built environment, our representations often do not factor how individuals and social groups non-homogenously *perceive and respond* to built environments. The aforementioned notion of 'place perspectives' is relevant for the conceptual cartography in section 'Representing the causal relevance of the built environment'. Individuals and social groups shape and are shaped by the built environment. There are various concepts worth exploring about how built environments regulate complex processes. For instance, built environment 'nudge'-based conceptual frameworks, relevant to public health, have been suggested (Pinter-Wollman et al., 2018). But even with the popularity of the nudge as an intervention tool during the pandemic, there are more adequate concepts to explore.

Representing the causal relevance of the built environment

How does the built environment, centrally, figure into the complex relations between biotic, social, and health processes? In this section, we discuss at least three conceptual developments that can be applied to the built environment: 'nudge', 'affordance', and 'interface'. The purpose of these concepts is to organize the multiple regulating functions of built environment contexts (BC's). We apply the concepts in order to show how BC's can be cohesively analyzed alongside social and biotic variables. This will set up our larger conceptual perspective—the built environment as an *interface that regulates multi-process pathways*. We conclude with the view that to adequately represent the various moderating roles of the built environment, we must acknowledge *who* ought to be involved in the process of representation.

Relationality and the built environment: built contexts and nudges. Built environments can 'nudge' human health choices and outcomes (Pinter-Wollman et al., 2018), such that cues in the environment can alter specific behaviors in predictable ways without forbidding options (Thaler and Sunstein, 2008; Oliver, 2017). For instance, Birnbach et al. (2010) found that in-line-of-vision hand sanitizer dispenser placement resulted in 53.8% of physicians sanitizing their hands, compared to doorway-adjacent dispenser placement, which resulted in 11.5% of physicians sanitizing their hands ($p = 0.0011$). Hygiene-related behaviors may be more susceptible to built environment nudges—a possible explanation being that COVID-19-related hand-washing behavior directly depends on personal perception of risk (Wise et al., 2020). Additionally, perceived-risk environmental cues can easily be manipulated into value-negative nudges ('sludges') to influence behaviors like stockpiling (Kim et al., 2020). Because of the effectiveness and causal linearity of certain behavioral modifications, nudges are surprisingly effective in explicit forms. Hygiene-related behavioral changes can be nudged by creating explicit informational interventions about COVID-19 (Krpan et al., 2021). We suggest that the 'nudge' provides an open conceptual infrastructure to represent public health behavioral modification; but we should be wary of the adequacy of the 'nudge' in accounting for the causal complexity of social and built environment contexts.

The first issue with the nudging conceptual framework pertains to social contexts. Nudged behavioral changes can be both mediated and moderated by other contextual social variables. For instance, extended social distancing history can reverse the positive effects of the aforementioned informational intervention nudges (Krpan et al., 2021). Even seemingly simple associations between risk perception and behavior are subject to complex relations: cultural context can modify certain types of risk perception, producing differences in risk-related behavior (Zeng et al., 2020). Representational frameworks that focus on nudges are problematic because, behind the appearance of causal linearity, complex social norms and contexts drive nudge effectiveness (Sunstein et al., 2019). For example, how can we adequately represent non-homogenous contexts, where social movement is successfully nudged for some and fully inhibited for others? During the pandemic, as a result of inconsistencies in policy decisions to announce mask mandates and the atmosphere of xenophobia, a contradictory context emerged for Asian Americans: There was discrimination and violence as a function of both choice pathways—wearing a mask vs. not wearing a mask (Han, 2021; Choi and Lee, 2021). That is, Asian Americans neither had the option of wearing a mask in public (for fear of appearing symptomatic) nor the option of not wearing a mask in public (for fear of appearing negligent) (Han, 2021; Choi and Lee, 2021). In such a context of absent options, any mask-related nudging policy will fully discourage movement through built environments for some, while smoothly encouraging that behavior for others.

A given nudge can be incorporated into an artifact—whether technological, built environment, or a simple object—to promote unconscious priming (Tromp et al., 2011). This compliments Olszewska and Konecka's (2020) argument that there is no such thing as a neutral built environment nudge. This is quite interesting because the implication is that built contexts, *intrinsically*, possess nudge capacity. We agree with the general suggestion that the built environment should be evaluated for non-neutrality in unconscious priming; but we disagree that the 'nudge' is an adequate concept to explain the various forms of causal relevance at the intersections between built environments and human behavioral changes. Built environment nudges can be more complex than in-sight hand sanitizer and 6-foot-distancing markers. Additionally, we argue that built environment nudges are not intrinsic but, rather, relational. That is, context modifies the causality of a given built environment nudge. For instance, priming effects differ, drastically, depending on social context, as well as 'self-construal'—the implicit and explicit representation of relations between self and others (Evans, 2008; Cash et al., 2017). 'Self-construal' is fascinating because it depends on the representation of oneself relative to a given social norm; and such relative social location can regulate the effectiveness of nudge priming, delivered through environmental cues (Cash et al., 2017). So, because priming through environmental cues can be moderated by sense of self, self-construal, and social norms, we suggest that explicit representational attention should be paid to *how contexts shape relations* between built environment cues, social processes, and public health behaviors.

Relevant to social contexts, a policy reliance on nudging has been used side-by-side with concepts like 'behavioral fatigue'—almost to a comical degree—in order to both explain and intervene in a wide variety of COVID-related health behaviors (Sibony, 2020). However, we warn that basing health policy decisions on the representational linearity of the 'nudge' glosses over the complexity of public health behavioral modifications. Namely, complex interactions produce emergent behavioral effects that might dilute or scatter behavioral interventions. For example, how do we explain and intervene in pandemic lockdown non-compliance? In some instances, policy relied on simple nudges to minimize 'behavioral fatigue'—with little success due to a misrepresentation of causes (Sibony, 2020). When contextual variables were represented, a more adequate causal explanation (than 'behavioral fatigue') emerged: reactance in combination with optimism bias can produce *interaction effects* that cause non-compliance (Sibony, 2020). Social context becomes even more complicated and non-homogenous when we consider that belief systems, associated with 'reactant' attitudes, can be correlated with geographical regions, in addition to increases in COVID-19 transmission (Kapitány-Fövény and Sulyok, 2020). As discussed in section 'Developing a relation-based representational precedent', relationships between belief systems and environments are relevant to transmission rates. But the further implication for nudging is that mitigating transmission rates depends on successful nudge planning that can address *differential social contexts*. We caution that misrepresenting public health changes as a function of implicit nudges may produce ineffective public health interventions that gloss over contextual complexities.

Recall that we began this discussion with a general problem: To what extent do current scientific practices fail to robustly account for the complex intersections between built, biotic, social, and health processes? But it isn't just 'representation' that is the issue, it is also 'intervention'. To add onto the list of three representational problems from section 'Diagnosing representational framework inadequacy: epistemological, ontological, and methodological problems'—Measurement Outcome, Representational Framework, and Surrogate—there is a further problem, due to causal misrepresentation in nudge frameworks:

Idealized intervention problem. The use of an inadequate causal representation that oversimplifies or homogenizes changing *interactions* between social, built, biotic, and health processes, in addition to the resulting oversimplification of emergent properties from such interactions, can result in inadequate public health interventions.

To summarize, we make the specification that 'nudging' provides an incomplete representational framework for built environment and social contexts by idealizing causal connections. Nudges rely on homogenized behavioral modifications through heuristic, linear, desire-based choice interventions, often missing the contexts that serve as substrates to regulate the effectiveness of the nudge. We believe that the regulating functions of the built environment constitute deeper interactions than a simple opt-in vs. opt-out. The built environment organizes causal factors that can serve as mediators and moderators (sometimes, both) of larger processes. We address this in the next section.

Relationality and the built environment: contexts and affordances. In section 'Diagnosing representational framework inadequacy: epistemological, ontological, and methodological problems', we presented a number of unacknowledged process-intersections that require a new representational infrastructure. The purpose of an adequate representational infrastructure is to broaden ontology, epistemology, and methodology in COVID-19 investigation. 'Nudging' infrastructure—with a focus on linear causal relations between BC's, behavioral changes, and health outcomes—misses the ontological contextuality of representing how behavioral changes operate within a given built environment. There are at least three interrelated concepts, relevant to a more adequate representational infrastructure: 'context', 'affordance', and 'interface'. We detail the first two in this section, before visualizing the third in the next.

In section 'Developing a relation-based representational precedent', we introduce that a given 'place' is ontologically complex, consisting of a *series* of contexts that organize physical and social interactions (Gerson and Gerson, 1976): contexts can determine social movement, rate of interactions, transmission of information, and value system changes (Gerson and Gerson, 1976, pp. 198–201). This is relevant for improving the conceptual backbones behind models. For instance, earlier we described the Arthur et al. (2021) model. It is worth exploring whether the parameters that constitute 'optimal contact rate'—i.e., the utility function, parameterized by perceived risks and benefits of social contacts—can take differential form, depending on the interactions that constitute a given context. Recall, for example, that cultural context can modify certain types of risk perception and risk-related behavior (Zeng et al., 2020). To be explanatorily and predictively useful, the Arthur et al. (2021) model may require modification to account for how parameters change as a function of built environment and social contexts. The representational importance of 'place perspective' is that, generally, it highlights emergent causality; but it is important to be precise about the causal role(s) constituted by contexts.

If we take seriously Olszewska and Konecka's (2020) claim that built environment contexts (BC's) cannot be causally neutral, then we can begin to explore more precise BC causal propensities. But to understand how such propensities can reside 'in' the built environment requires a sophisticated conceptual infrastructure: 'affordance'. Affordances are constituted by *relational* properties that emerge from the *interactions* between individuals/groups and objects, processes, or environments—such that the relationality produces 'capacities for action'—including, promotion and inhibition of behavioral pathways (Davis, 2020).

A key benefit of the affordance framework is that it can be used to represent how public health behaviors are not homogenously promoted within built environment contexts. That is, environment-to-person interactions within a given place can produce different sets of affordances for both individuals and social groups. It is important to note that a given affordance is not merely a 'perception' or 'subjective experience' (Davis, 2020). Rather, we take affordances to constitute *causal pathways that can operate differentially* within a given place.

This type of relationality is ignored in the 'nudge' conceptual framework and public health policy that uses the nudge framework. For instance, often unacknowledged at the policy level but faced by residents, environmental racism drastically alters the capacity for "healthy movement" nudges in contexts of inequitable public park regulation and polluted environments (Mitra et al., 2020; Burrowes, 2020). In other words, the nudge for health-related movement becomes impossible within the context of environmental racism.

Regional studies track multiple pollution zoning parameters—e.g., PM, SOX, VOC—to document how permitted polluting sites disproportionately affect people of color, creating new forms of neighborhood redlining (PQC, 2020). Other studies yield deeper causal analysis pertaining to pollution—namely, that general car emission pollution decreases in COVID-19 have concealed industrial pollution increases that disproportionately affect long-term $PM_{2.5}$ exposure in Black communities (Terrell and James, 2020). Novel concepts emerge to characterize pollution disparities as a function of structural racism—e.g., 'pollution burden' (PQC, 2020; Terrell and James, 2020). Such concepts can be embedded within the affordance framework. *Built environment burden* is not just disproportionate exposure to pollutants within a given built environment context. Rather, built environment burden can constitute numerous BC affordances. For example, Louisiana's industrialized regions have been shown to hold significant associations between long-term $PM_{2.5}$ exposure, social stressors, and COVID-19 morbidity and mortality in Black residents (Terrell and James, 2020). Here, the industrialized region BC can be represented as regulating social and public health burdens. To make the causal language precise, a given BC can *moderate* health processes at many scales—such as, BC moderation of environmental pollutants, as well as other social determinants of health that promote multiple pro-inflammatory mechanisms, e.g., via IL-8 Signaling, NF-κB Signaling, and Dendritic Cell Maturation (Gaye et al., 2017; see section 'Diagnosing representational framework inadequacy: epistemological, ontological, and methodological problems'). Notice here that we are using 'affordance' broader than the original action-based framework. 'Affordances' can be conceptualized as *public health capacities occurring at many scales within a given context.* Some of those capacities are behavioral or action-based, and they can also be entangled with capacities at other scales.

A given BC can also *inhibit* numerous beneficial public health capacities by preventing and discouraging access to beneficial resources. We often fail to acknowledge the sharp lines of disproportionate built environment obstructions in natural environments—such that, in addition to pollution pathways being amplified, biotic system pathways are muffled. For instance, in pandemic contexts our representational focus has been fine-tuned to transmission in BC's to such an extent that we often fail to explore the representation of resilience-promotion (and inhibition) by the built environment. Quite obviously, it has been extensively researched that most residential and commercial HVAC systems are poorly equipped for virus particle filtration.[3] However, further representing built environment promotion and inhibition becomes critical in dense cities where a combination of factors may force residents to keep their windows shut, relying almost solely on central heating and cooling systems. Additionally, where affordances for social movement are limited or absent, understanding the regulatory roles of the built environment becomes essential. We suggest that in pandemic contexts, health-promoting airflow representation has taken on a new relevance. Perplexingly, indoor airflow processes are rarely considered in policy-planning relevant to the built environment and public health (Chrysikou, 2018). Furthermore, various considerations in airflow are rarely amalgamated in public policy-related built environment representations and interventions. However, general intervention in health-promoting mechanical airflow systems requires detailed representation of how the built environment regulates multifarious processes—e.g., energy, oxygen, and harmful and beneficial microbes.[4] For instance, central HVAC systems, even at ideal function, can create unsuitable health environments because they eliminate diversity of bacteria and create human disease-centered colonies (Kembel et al., 2012).[5] Through the elimination of bacteria diversity, there is the concern that central HVAC systems create harmful microbe pumps, but we suggest that there is a deeper concern about inhibiting beneficial bacteria that may provide protective health against lung-related diseases—such as, bacteria from the Firmicutes genera (Sokolowska et al., 2018).[6] HVAC system design that maximizes bacteria diversity, thereby promoting lung resiliency, has so far been fully unexplored in COVID-19 investigation; and thus, this is currently an *unacknowledged causal nexus*. This is why broader representational approaches are needed: Health-negating factors can be represented along with resilience-promoting factors—e.g., naturally occurring bacteria profiles that minimize lung inflammation.[7] Even in something as seemingly obvious as built environment airflow moderation, *expanding the representational scope* over processes beyond transmission could prove fruitful. Additionally, consistent with the discussion in section 'Developing a relation-based representational precedent', we suggest that amalgamating multi-process considerations is closely tied to developing new interdisciplinary and transdisciplinary practices—a point that we further illustrate in the next section. That is, the built environment regulates numerous processes; and only when we synthesize disciplinary lenses, do we begin to uncover more process-intersections. By taking wider microbiology, systems biology, architecture and design, logistics, and economic modeling approaches to airflow processes, we can reveal unaccounted-for relations that are relevant to population health. Interdisciplinary opportunities to take a new perspective on airflow are present but seldom integrated into causal analysis of the built environment. For instance, recent fields like 'pyroaerobiology' have emerged to investigate wildfire and airflow mediation of microbes (Kobziar et al., 2018; Moore et al., 2021). Our suggestion is that future investigation of built environment regulatory roles could benefit from disciplinary interactions with seemingly peripheral fields like pyroaerobiology—e.g., in order to study PM mediation and moderation of microbes between ecological and built environments.

To summarize, the affordance framework can be used to represent *multiple causal pathways that can operate differentially* within a given place—e.g., in the form of dual representations of amplified 'built environment burden' and inhibition of beneficial biotic access. We propose that the 'affordance' conceptual framework offers the starting steps for the representation of built contexts by creating a structure that focuses on *interactions*. The next step is to summarize the regulating functions of the built environment in a cohesive visual representation. Visual models, heuristics, and metaphors can restructure ontology, while also presenting new epistemological and methodological avenues.

Relationality and the built environment: visualizing interactions and interfaces. We return to the issues presented in section 'Diagnosing representational framework inadequacy: epistemological, ontological, and methodological problems' in order to make final suggestions about *how* representations can be constructed and *who* ought to have a role in shaping representations. In this section, by specifying visual metaphors and diagrammatic methods, we aim to create useful conceptual pathways for the exploration of ontological, epistemological, and methodological frameworks relevant to studying the built environment.

So far, all of the visual representations in our discussion contain epistemological and ontological infrastructure limitations. For instance, Fig. 1 is limited because it idealizes points of intersection between processes. The multi-process interactions discussed in section 'Relationality and the built environment: contexts and affordances' are numerous, continuous, and operate on multiple scales. Also limited, Fig. 2 has the potential to embed multifactorial moderation and mediation; but the representational format risks simplifying built environment processes to single factors. Furthermore, there is no representational capacity to show how variable relations change as a function of contexts. The diagrammatic styles in Figs. 1 and 2 have other general limitations. They present little possibility for quantification, as well as representing multiple dimensions. So, perhaps there is a more adequate type of visualization that can capture important features of built, biotic, social, and health interactions. Our focus on 'interactions' makes the affordance conceptual framework amenable to a three-dimensional visual representation that can embed relationships between multiple variables. We suggest a number of conceptual avenues to representing process-interactions in 3D.

In the philosophy of biology, hypersurface representations have received considerable attention (Fusco et al., 2014), traceable to Wright's (1932) and Waddington's (1939; 1940; 1957) iconic 'landscape'-style representations. For Waddington, the three-dimensional landscape emerged out of an attempt to conceptualize an *explanatory* framework that could ontologically house numerous organizational structures and functions of biological development. Our purpose for discussing visual representation is similar to his: adequate visual representations can *restructure ontology* and *facilitate new methodological routes*. For Waddington (1939; 1940; 1957), a biological system's developmental pathways and states are akin to a marble rolling through a three-dimensional manifold. A marble moves from flat undifferentiated states to differentiated depressions, which represent alternative developmental states. The tension of the manifold slopes is determined by many interconnected gene products, or in a modern perspective—'gene regulatory networks'—that are attached to peg-like genes. We believe that Waddington's landscape metaphor is particularly fascinating because it can capture *emergent* properties—such as, 'restriction' and 'differentiation'—which are greater than the sum of their components.

Similarly, because of the complexity of affordances, emergent properties relevant to differential built environment burden and inequitable health outcomes can begin to take three-dimensional representational form. That is, the built environment can be represented as more than just the value of a single variable. Recall that built environment representational choices often amount to just a single discrete variable or handful of variables—with limited focus on interaction and context (Clifton and Perez, 2015; Hamidi et al., 2020). Here, ontology is limited by representational framework choice. The built environment can be represented as a set of causal factors, but we suggest that it can also be represented as an *interface* that reorganizes causal relations—concurrently, deregulating factors, while leaving others unaffected. A change in interface topography can modify multiple factors. Visual metaphors, like Waddington's landscape, can be scientifically useful for the development of more technical forms of representation. As a starting step for our more complex visualizations, we represent the built environment as an interface that regulates multiple variables (e.g., a set of biotic variables), while being shaped by other variables (e.g., a set of social-systemic variables). Imagine this interface as a catalyzing membrane whose causal topography can be co-modified based on its interactions (Fig. 3). In the hand-crafted illustration in Fig. 3, we visualize the built environment behaving dynamically, like fascia within the architecture of physiology. Notably, in the interdisciplinary research on fascia, there is a shift away "…from a body made up of *parts* to the *wholeness of the architecture* holding them together" (Dumit and O'Connor, 2015, p. 1 our emphasis). Additionally, fascia has mediating and moderating roles, while also being shaped by other factors (Findley and Shalwala, 2013; Dumit and O'Connor, 2015; Dumit and O'Connor, 2016). As Dumit and O'Connor (2015) state, "Fascia can be described as a biomatrix that surrounds everything in our bodies, connects everything, and yet paradoxically cleaves and separates everything" (p. 1). It is also structurally responsive to changing interactions (Dumit and O'Connor, 2016). Finally, fascia maintains state flexibility (e.g., on a continuum between solid and liquid states) and produces emergent properties that are greater than the sum of their parts (Dumit and O'Connor, 2015). Similarly, we illustrate the built environment as a co-modifiable matrix with moderating functions (Fig. 3). Why go through all of the trouble of creating a metaphor for the built environment? We think that such metaphors can direct scientific attention to the multifaceted roles of the built environment. The visualized interface—that reorganizes, connects, promotes, erodes, and inhibits pathways—spotlights key causal roles of built environments. As an exercise in representational versatility, there are options to explore the metaphor further—e.g., by spotlighting landscape connections. For instance, in Fig. 4 we take the reductionistic approach of Fig. 2 in order to idealize the built environment interface as individual built environment factors and their causal relevance to two multivariable landscapes. To reiterate, visualizations, like Waddington's landscape or the built environment interface (Figs. 3 and 4), can be useful for the illustration of general causal roles, relationships, and properties, which can be further explored in more technical forms of representation.

Choice in scientific representation requires emphasizing certain factors while idealizing others (van Fraassen, 2008; Keyser and Howland, 2020). Often, our scientific focal point can be shaped by practical considerations. The physiology of fascia had received little attention and had not been represented in textbook diagrams because disease in fascia had not been a key medical concern—simply put, "…you don't die from fascia" (Dumit and O'Connor, 2015, p. 1). As a parallel, we think that the built environment's causal import on other processes has received little attention, but not because "you don't die from the built environment". Rather, it is because the various moderating roles of the built environment on public health factors have been causally opaque or oversimplified for practical purposes.

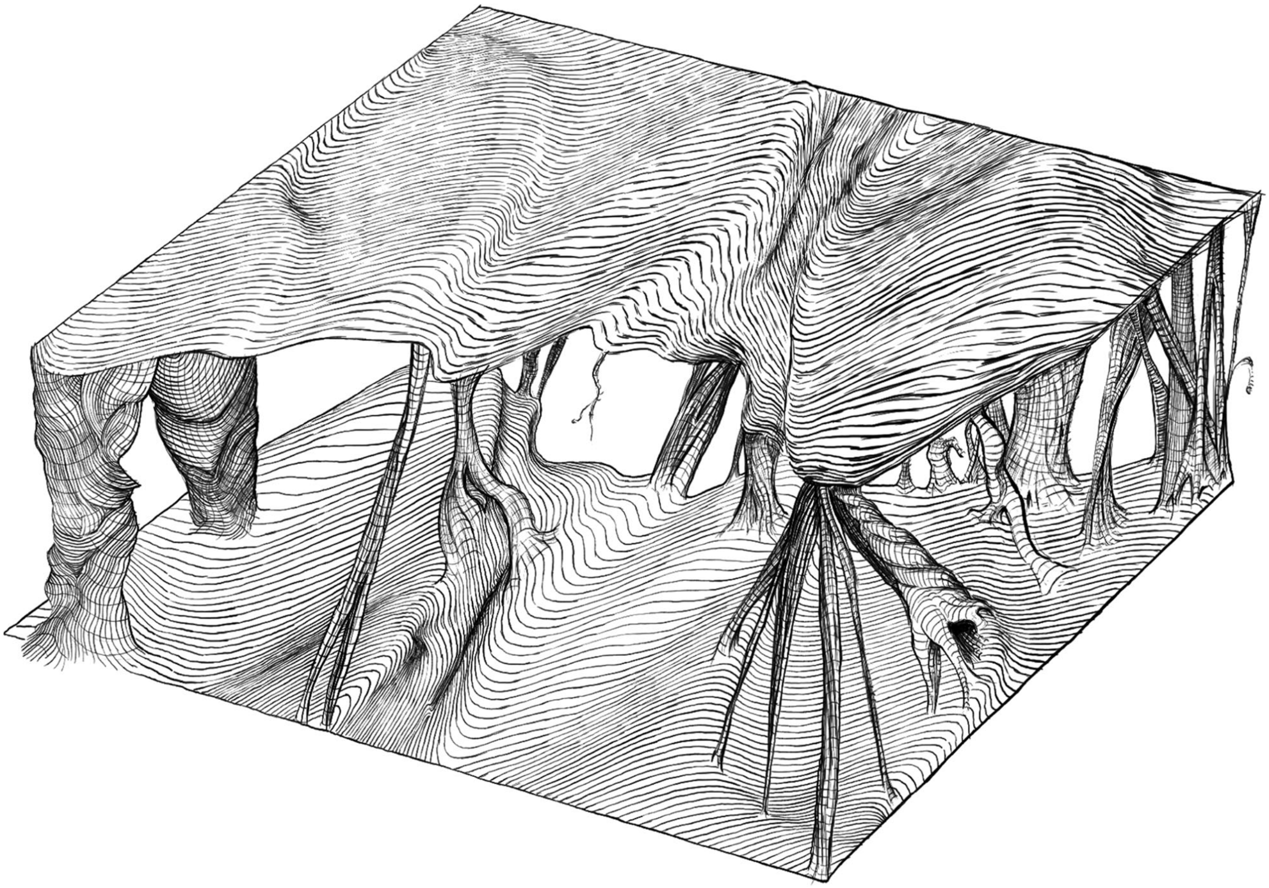

Fig. 3 Built environment as interface. Metaphors can restructure ontology, while also presenting new epistemological and methodological avenues. As a starting step for our more complex visualizations (Figs. 4 and 5), we present a hand-drawn representation of the built environment, behaving as an *interface* that regulates the interconnections between two multivariable landscapes, while being shaped by each landscape. Here, each set of causally relevant variables is represented as its own landscape (e.g., social, biotic, or health landscape). The built environment interface is represented as a catalyzing membrane whose causal topography can be co-modified based on its interactions. The interface reorganizes, connects, promotes, erodes, and inhibits pathways. This general conceptual precedent opens avenues for the analysis of specific concepts relevant for understanding the moderating and mediating functions of the built environment—e.g., 'nudge', 'affordance', 'interface', and 'context'.

The importance of Waddington's version and new versions of 'landscape' diagrams, as organizational tools, is in the representation of relationships between multiple variables (Fusco et al., 2014). For instance, as depicted in Fig. 5, a large number of dimensions can be represented in a smaller hypersurface, where a set of independent variables determines dimension *n* (Fusco et al., 2014). Generally, this type of landscape is a mathematical function that associates values of a set of independent variables with the value of a dependent variable over a Euclidean space (Fusco et al., 2014, p. 115). Landscapes can also be translated into dynamical systems—although, with limitations as well as asymmetry in moving from dynamical systems to landscapes (Fusco et al., 2014, p. 116). For our use, the general representational purpose of a landscape is to depict the relations between multiple variables. A description of the time evolution can be supplementary.

The built environment can be represented as an independent variable with other independent variables representing biotic or social factors, and the dependent variable representing a given health outcome (Fig. 5). However, we also suggest that the built environment can be turned into its own landscape—for instance, by representing the variables involved in a particular type of built environment burden. We propose that this adaptable landscape structure (Fig. 5) allows for two useful diagrammatic methods in the representation of the built environment.

First, this landscape structure promotes a flexible transition between multidimensional diagrams (Fig. 5) and surrogacy wiring diagrams (Fig. 2) to suit shifting *explanatory* demands. This provides versatility in representing complex relationships while being able to selectively depict certain features of the built environment for pragmatic purposes. Depending on the explanatory need, built environment burden can be represented as a multivariable landscape, series of landscapes, or it can be reduced to a single node within a wiring diagram. But importantly, we suggest beginning with complexity, rather than beginning with idealization, in order to avoid the *surrogate measure problem* described in section 'Diagnosing representational framework inadequacy: epistemological, ontological, and methodological problems'. After all, part of the practical challenge is how to represent multifarious processes—built, social, biotic, and health—cohesively, but also, flexibly.

Second, with the use of this diagrammatic structure the built environment can be analyzed together with other multivariable landscapes in order to explore landscape connections. In robust data contexts, this can begin with the analysis of associations between the surfaces of multiple planes. In contexts with limited interdisciplinary data, this can prompt further empirical investigation of causal relationships between landscape variables. For instance, co-modification between social and built landscapes requires detailed analysis and empirical investigation. Social

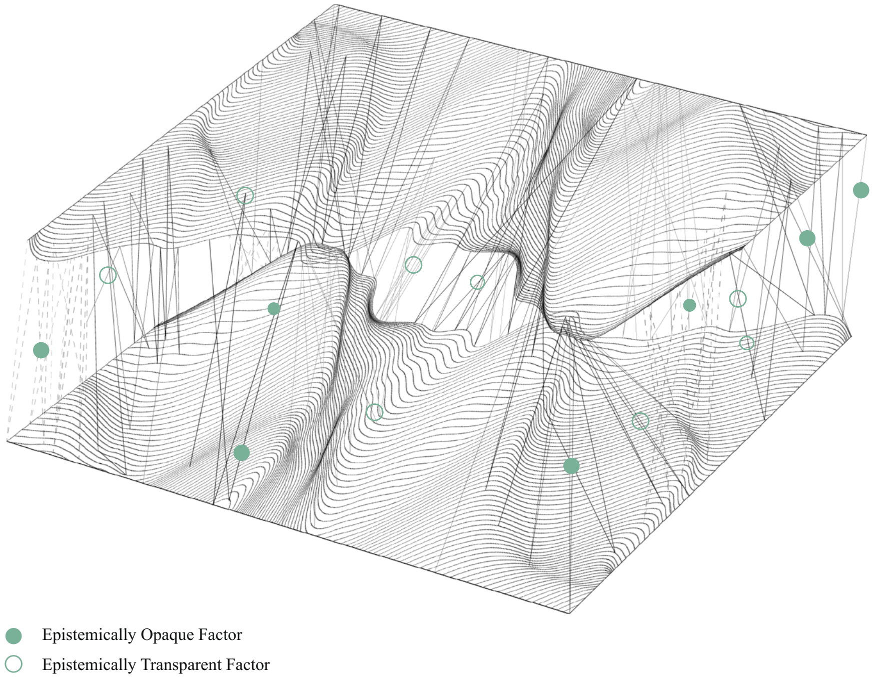

Fig. 4 Landscape connections. Understanding the various causal roles of the built environment can illuminate the relations between multiple landscapes. Here, the built environment interface is reduced to built environment *factors* and their causal relevance to two multivariable landscapes. Note: We idealize 'opaque' vs. 'transparent' factors because our illustrative focus is on landscape connections. However, more detailed characterizations can specify continuums of opacity and transparency—detailing nuances in identification, uncertainty, and weak vs. intrinsic/essential limitations.

landscapes can produce stark built environment disparities within a given place. Additionally, built and social landscapes can generate mutually reinforcing feedback loops. There are complicated relationships to explore—e.g., how social processes that create health disparities are further reinforced by inequitable built landscapes. Representing the accurate relations is paramount for understanding *how* built and social landscapes co-modify each other. Social landscapes can erode built landscapes over time, but they can also create quick, dramatic shifts in built landscapes—or both. For example, recent pseudo-environmental practices have resulted in pop-up toxic landfill sites, affecting Black and Latinx populations, while nearby White populations remain fully unburdened by permitted polluting sites (Fears, 2020). Importantly, such built environment sites are a continuation of a history of racist policies and built contexts. Something that is beyond the scope of this paper but could be an extension of our discussion is the application of multivariable landscape analysis for the purpose of clarifying the causal relationships in unfolding case studies. Within a general two-tier landscape diagram that shows the relationships between built and social landscapes, new iterations of systemic racist practices can be represented in detail by tracking how sudden multivariable spikes can deregulate a given health outcome. Newly formed toxic sites like 'Shingle Mountain', which is a six-story toxic site composed of particulate matter that took just six months to emerge, have created a compounded health hazard context (Fears, 2020). The topography of such contexts requires fine-grained multi-tiered causal analysis, otherwise we may risk an uninformative coarse-grained representation of average pollution levels within a homogenized built context—hiding patterns, similar to the aforementioned case study of industrial pollution spikes in a context of decreasing average pollution measures (section 'Relationality and the built environment: contexts and affordances') (Terrell and James, 2020).

It might seem obvious that multivariable interactions are important to analyze, just like it might seem obvious that built environment burdens, e.g., Shingle Mountain, receive adequate investigation into social and built process moderation. But this is false. Shingle Mountain emerged within six months, but it took years to be investigated and acknowledged by policymakers—only resulting as a function of unrelenting community efforts in data and advocacy (Fears, 2020). Illustrated by the Shingle Mountain example, *community efforts can reveal unacknowledged interactions* between built, social, and biotic processes. As we have discussed in section 'Diagnosing representational framework inadequacy: epistemological, ontological, and methodological problems', new research could benefit from a more robust conceptual framework that can shift ontological and methodological practices. We are advocating for greater causal resolution in *how* we represent complex relations between built and social landscapes. But there is a related issue about *who* represents complex relations.

Relationality and the built environment: community participation in measurement practice. This brings us to an important point about accuracy and equitability in scientific practice: Indexical measurement questions - e.g., who measures, how they measure, and what they measure - are essential for the development of more adequate measurement/data practices. For instance, who determines what counts as a 'relevant' built environment context? We conclude with a suggestion for specific methodological needs, one of which is to develop new measurement methods and collaborations between scientists and communities. We suggest that one method to avoid the conceptual and methodological pitfalls mentioned in the first part of this discussion is to clarify transdisciplinary terminology side-by-side with direct collaborative goals. Rashid et al. (2009) synthesize the complex causal factors for health disparities—e.g., purchasing power; insurance; geographic location; cultural factors; language barriers; racial bias; stereotyping; and systemic factors (social, political, and physical contexts) (Institute of Medicine, 2002; Institute of Medicine, 2003; Mead et al., 2009; Artinian et al., 2007; Agency for Healthcare Research and Quality, 2009); and they argue for the

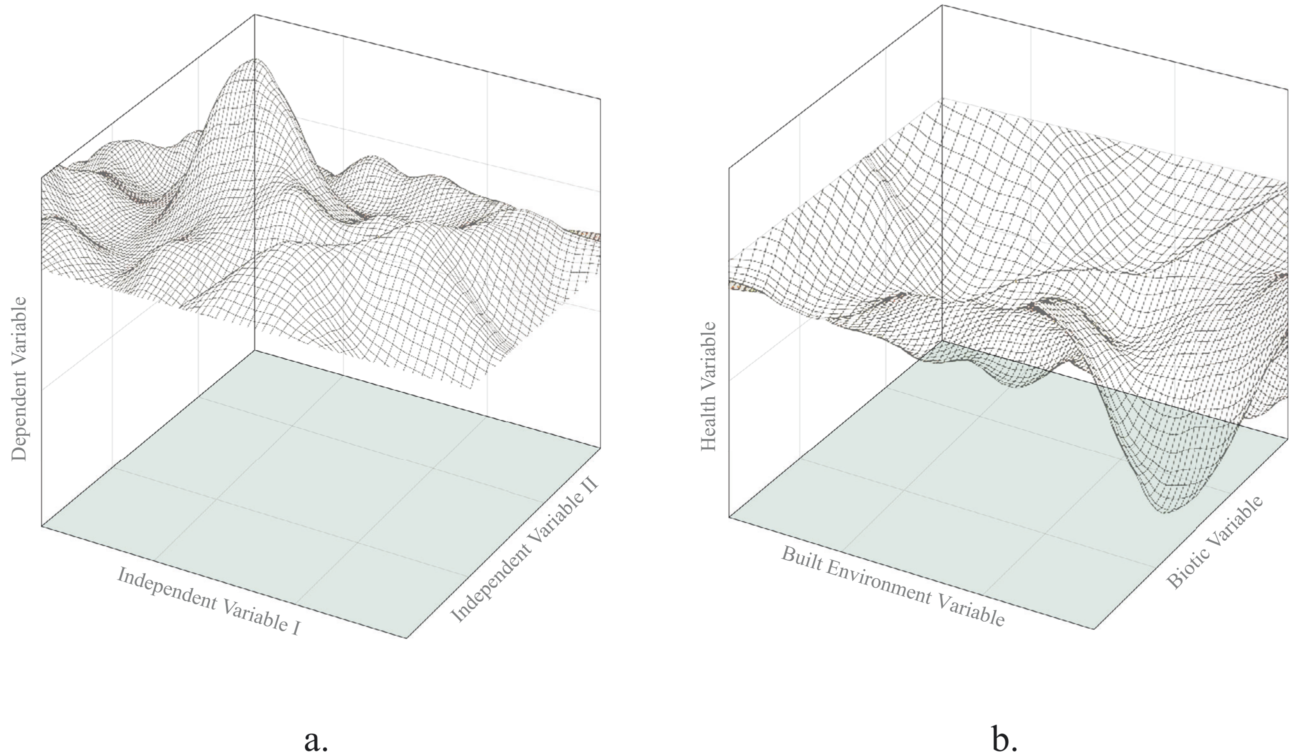

Fig. 5 Built environment scaler field diagrams. Extending beyond metaphorical representation, this figure depicts scaler field landscape representations—associating values of a set of independent variables with the value of a dependent variable (**a**). The built environment can be represented as an independent variable with other independent variables representing biotic or social factors, and the dependent variable representing a given health factor (**b**). But the built environment can also be turned into its own landscape, represented with multiple independent variables, such as the variables involved in 'built environment burden'. As we discuss, landscape connections can be explored through *associations* between the surfaces of multiple planes, and they can also prompt further *empirical investigation* of causal relationships between landscape variables.

continuation of transdisciplinary health research through cross-agency collaboration and public partnerships in order to investigate the complexities of health disparities and to disseminate solutions. Unfortunately, even when epistemically effective and fruitful, such collaborative structures between researchers and the public have been cut (Rashid et al., 2009). The relevant question here is, who has a say in diagnosing and shaping health environments?

Community measurement methods can emerge from direct need. For instance, because of a relative lack of air quality monitoring infrastructure in polluted communities, Gabrys et al. (2016) proposed a new paradigm for iterative data-production and analysis. In this case, public participation in measurement practice is consistent with reflexive approaches to engaged community measurement practices for the pursuit of environmental justice (Gabrys et al., 2016). The Gabrys et al. (2016) paradigm of measurement can be used to re-envision the role of community engagement in scientific practice. The same inventive approach, arising out of a need, can be applied to COVID-19 data-generation. New research programs could synthesize epidemiological data on COVID-19 outcomes and social determinants of health with qualitative data, based on firsthand accounts about social-systemic and built environment factors. We think that it is imperative to mention that the need for and value of qualitative data is a developing topic in public health (Hanlon et al., 2011). If community members can autonomously report qualitative data to scientists and policymakers, this not only builds a more robust data picture, but it can also promote social autonomy. Community narratives can be used to inform public health modeling and policy-making. Such approaches have been attempted by using community qualitative data to generate affordance maps (Lopes et al., 2018). We can structure and summarize the general method of public scientific measurement practice as follows.

Data-gathering and modeling can extend into the socio-technical collaborations between community members, scientists, and policymakers (Rashid et al., 2009; Gabrys et al., 2016). Through access to technology, community members can generate data, which can subsequently be analyzed and visualized into various data models, referred to by Gabrys et al. (2016) as "storying processes". On our account, these storying processes would focus on finding *new* relevant variables for built environment and social landscapes. For instance, Shingle Mountain causal variables and their subsequent health impacts were wholly reported by community members. Before this, representations of the built environment within the region were homogenized, ignoring the various causal roles of environmental racism. We think that the storying process can contribute to scientific practices—such as, the co-development of detailed ontological frameworks that address emergent properties like built environment burden, or the creation of new data methods for the purpose of generating values for key variables. We conclude with a suggestion that the coordinated activity between multiple measurement perspectives can be expanded to include *independent* perspectives, generated by communities. These perspectives can be used for changes in intervention approaches (e.g., how communities intervene in pandemic contexts and beyond), as well as theory-building practices (e.g., how communities reveal key, unacknowledged processes-intersections). This type of iterative measurement process requires coordination between independent perspectives, including—scientists, communities, technological systems, and policymakers.

Two things are important to note here. First, there is a technological challenge. Community engagement in the measurement process requires technological platforms for generation, organization, and dissemination of data. A given community can generate diverse data—through the creation of firsthand accounts, photographs, visuals, parameterized data sets, etc.; but equitable technological tools have to be provided as organizational platforms for the data. From a design standpoint, a possible start is to investigate the structure and equitability of technological platforms that provide real-time community-submitted data. The second thing worth noting about community participation in measurement practice is that data generation and storying methods indicate "responsibilities" that emerge from interacting with data (Bell, 2015, p. 19). We make a more general point: Measurement practice choices are deeply entangled with normative considerations. That is, re-envisioning the coordination between scientists, communities, and technological measurement tools will require understanding new responsibilities in how we interact as part of the measurement process, as well as what kinds of measurements matter to what parties.

Concluding remarks

We have presented multiple problems in COVID-19 scientific practice that can be reduced to the following issue: to what extent do current measurement and data practices fail to robustly account for the complex *intersections* between built, biotic, social, and health processes (section 'Diagnosing representational framework inadequacy: epistemological, ontological, and methodological problems)'? To confront this general issue, we have presented a representational precedent that focuses on '*relations*' (section 'Developing a relation-based representational precedent'). Additionally, we have analyzed at least three conceptual developments that can be applied to the built environment: 'nudge', 'affordance,' and 'interface' (section 'Representing the causal relevance of the built environment'). The purpose of these concepts is to *organize the multiple regulating* functions of built environment contexts (BC's). We have applied these concepts in order to show how BC's can be cohesively analyzed alongside social, biotic, and health landscapes. Our main point is that the built environment can be represented not only as a single discrete variable (or handful of variables) but also as an *interface* that reorganizes causal relations—concurrently, deregulating factors, while leaving others unaffected. By clarifying the unacknowledged moderating roles of the built environment, we hope to inspire new conceptual and practical developments that broaden ontology, epistemology, and methodology in COVID-19 and beyond.

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Notes

1 High sensitivity conditions refer to minimizing false negatives, such that a given measure often achieves an expected value relative to a proximate clinical endpoint. High specificity refers to minimizing false positives, such that a given measure rarely achieves an expected value relative to absent clinical endpoint.

2 Whitmee et al. (2015) explicate the complexity and quality of health, social, ecological relations. They describe degrading health outcomes as a function of "inequitable, inefficient, and unsustainable patterns" in resources, environment, and technology (Whitmee et al., 2015, p. 1973).

3 Most residential and commercial HVAC systems require a minimum MERV of 8, which is measured to capture 70-85% of particles, with a range of 3.0–10.0 μm. But in aerosolized particle form, SARS-CoV-2 has been measured between 0.25 to 0.5 μm (Liu et al., 2020).

4 Broader representational frameworks can even be useful when applied to the most seemingly obvious airflow considerations. Transmission and energy are rarely synthesized within a single representational framework, directed toward public-policy interventions. Virus spread can be minimized by increased outdoor air fractions; however, this has the tradeoff of increasing energy supply and maintenance cost—the latter of which is often the focus in public and residential built contexts (Dietz et al., 2020). But if we consider transmission and energy efficiency within a multi-process representation, an intervention dilemma emerges: whether to maximize air fraction and virus particle filtration at the expense of leaking energy and maintenance supply—i.e., transmission-minimizing interventions are pinned against efficiency-promoting interventions. There are numerous practical airflow dilemmas if we consider multi-process pathways. For example, elevated humidity decreases virus spread; but the standard HVAC design prevents humidity moderation: Most HVAC systems do not have indoor humidification due to maintenance difficulty and risk of over-humidification, which causes mold growth. The dilemma is whether to include humidification in HVAC technological development, thus minimizing virus particle viability, but potentially creating maintenance breakdowns and mold hazards. Built environment dilemmas can be uncovered if we *broaden representational scope* in order to reveal process-intersections.

5 As National Academies of Sciences, Engineering, and Medicine (2017) thoroughly outlines, U.S. single-family residential HVAC systems "rarely incorporate outdoor air intake but instead recirculate interior air primarily for temperature control, typically with low-efficiency particle filtration". Often there is an increase in microbe distribution, e.g., through humidification systems and mechanical ventilation, rooftop HVAC components near standing water, and high-pressure differentials that influence interior microbial pathways via "stack effect" (National Academies of Sciences, Engineering, and Medicine, 2017).

6 In a causal manipulation on mice, once mice were inoculated with these four bacteria, airway passage inflammation decreased (Arrieta et al., 2015).

7 Further research questions about unacknowledged process-intersections arise: How does pollution due to inequitable built environments interact with bacteria in airflow to produce non-resilience in overall physiological health? Research programs can investigate the intersections between built environment, microbiomes, pollution, and social processes. For example, Alderete et al. (2018), show that there is a causal connection between air pollution exposure in adolescents and microbiome changes. Specifically, there is a connection between air pollution and increases in *Bacteroidaceae* and *Corynebacteriaceae*—both have been associated with intestinal inflammation, obesity, insulin resistance, and altered metabolism (Alderete et al., 2018).

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Ethical approval

Ethical approval is not applicable since this article does not contain any studies with human participants performed by any of the authors.

Informed consent

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Additional information

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