PERSPECTIVE

Perspective: A Framework for Addressing Dynamic Food Consumption Processes

Jennifer C Taylor,[1,2] Margaret Allman-Farinelli,[3] Juliana Chen,[3] Julia M Gauglitz,[4] Dina Hamideh,[4] Marta M Jankowska,[5] Abigail J Johnson,[6] Anna Rangan,[3] Donna Spruijt-Metz,[7] Jiue-An Yang,[5] and Eric Hekler[1,2]

[1] The Design Lab, University of California, San Diego, San Diego, CA, USA; [2] Herbert Wertheim School of Public Health and Human Longevity Science, University of California, San Diego, San Diego, CA, USA; [3] Charles Perkins Centre, University of Sydney, Sydney, Australia; [4] Skaggs School of Pharmacy & Pharmaceutical Sciences, University of California, San Diego, San Diego, CA, USA; [5] Department of Population Sciences, Beckman Research Institute of City of Hope, Duarte, CA, USA; [6] Division of Epidemiology and Community Health, University of Minnesota, Minneapolis, MN, USA; and [7] Center for Economic and Social Research, University of Southern California, Los Angeles, CA, USA

ABSTRACT

The study of food consumption, diet, and related concepts is motivated by diverse goals, including understanding why food consumption impacts our health, and why we eat the foods we do. These varied motivations can make it challenging to define and measure consumption, as it can be specified across nearly infinite dimensions—from micronutrients to carbon footprint to food preparation. This challenge is amplified by the dynamic nature of food consumption processes, with the underlying phenomena of interest often based on the nature of repeated interactions with food occurring over time. This complexity underscores a need to not only improve how we measure food consumption but is also a call to support theoreticians in better specifying what, how, and why food consumption occurs as part of processes, as a prerequisite step to rigorous measurement. The purpose of this Perspective article is to offer a framework, the consumption process framework, as a tool that researchers in a theoretician role can use to support these more robust definitions of consumption processes. In doing so, the framework invites theoreticians to be a bridge between practitioners who wish to measure various aspects of food consumption and methodologists who can develop measurement protocols and technologies that can support measurement when consumption processes are clearly defined. In the paper we justify the need for such a framework, introduce the consumption process framework, illustrate the framework via a use case, and discuss existing technologies that enable the use of this framework and, by extension, more rigorous study of consumption. This consumption process framework demonstrates how theoreticians could fundamentally shift how food consumption is defined and measured towards more rigorous study of what, how, and why food is eaten as part of dynamic processes and a deeper understanding of linkages between behavior, food, and health. *Adv Nutr* 2022;13:992–1008.

Statement of Significance: This framework provides a practical set of definitions and steps to support theoreticians in conceptualizing food consumption processes, to study these phenomena in their full complexity. By more explicitly defining consumption as part of processes, this framework invites transdisciplinary approaches and broadened definitions of diet, eating, and related concepts.

Keywords: eating behavior, food consumption, diet, precision nutrition, dietary assessment, food logging, food systems, dynamics, systems science, precision health

Introduction

Dietary and food consumption actions of individuals and communities have a profound impact on individual (1, 2), societal (3, 4), and planetary health (5, 6). As the scale of the influence of food consumption implies, these actions do not occur in a vacuum and, instead, take place in cultural, ecological, political, and economic contexts that influence individual actions, with individual and community actions influencing these contexts (3, 4). Given this, fields such as the nutritional and behavioral sciences increasingly recognize the limits of current approaches for studying food consumption, with calls for more rigorous measurement and holistic definitions that address the myriad ways consumption interacts with health, food security, and other areas (7, 8). Most methods currently used to study food consumption approach consumption as a "thing," with the goal of defining *what* food consumption is in isolation, rather than approaching consumption as part of complex adaptive systems, which defines consumption as an integral part of dynamic processes of adaptation (9, 10). There is a pressing

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need to shift how we conceptualize food consumption, from a reductive *thing* formulation to a systems-oriented *processes of adaptation* orientation, to effectively address the complexity of food and eating.

The need to shift from a *thing* to a *processes of adaptation* orientation can be understood with a cursory examination of the core concept of "diet." The *Oxford Dictionary* defines diet as "the kinds of food that a person, animal, or community habitually eats," implying diet is less about instances of eating and more about patterns of what people "habitually" eat over time and context. Of course, there are other important potential foci relevant to consumption, such as abrupt changes in meal timing associated with a holiday break, gradual changes in fluid intake during transitions from cooler to warmer seasons, or the impact consumption choices have on natural ecosystems. To recognize the implicit limitations of diet, scientifically, we use the term "consumption" to invite broader conceptualizations of what, how, and why food is eaten.

This shift to focus on processes of adaptation is possible with emerging technologies. The wide and growing adoption of smartphones, wearables, and in-home devices and the introduction of smaller and more affordable wearable sensors together present opportunities for continuous, real-time monitoring of consumption related to facets such as behaviors, physiological states, and context (11, 12). While these technologies afford new possibilities for measuring consumption in context, many of the measurement protocols devised using these technologies build on prior conceptualizations of consumption, based on nondynamic dietary assessment approaches. For example, newer technologies using digital images to capture food consumption follow a similar protocol as traditional paper-based food records (13, 14). While there are good reasons to build on prior approaches, such as supporting knowledge accumulation, there are also potential unintended consequences. In particular, the likely mismatch between the inherent complexity of what, how, and why we eat and the relative simplicity of measurement protocols could easily obfuscate rather than elucidate our understanding of processes of consumption (15, 16).

The purpose of this paper is to offer a framework, the consumption process framework (**Table 1**), to approach conceptualizations of food consumption as processes of adaptation. Our primary audience is what we label theoreticians, with a secondary audience of methodologists, and a tertiary target of practitioners, with these audiences together supporting research that bridges theory and practice (see **Figure 1**). These 3 audiences define roles that support research bridging theory and practice, with the potential for any one person to operate in more than 1 role. We define "theoreticians" as those who seek to provide complex adaptive systems conceptualizations of food consumption to guide practice. As an analogy, these theoreticians are like theoretical physicists. Within physics, theoretical physicists postulate robust conceptualizations and predictions about complex phenomena, mostly in the form of mathematical equations and computational models, which can be vetted and tested by empirical physicists, with the 2 groups working synergistically together to advance the field of physics. The consumption process framework is meant to provide a starting point for those interested in postulating robust, empirically justifiable, and testable conceptualizations of food consumption processes that support pragmatic goals of advancing individual, societal, and planetary health. This role requires the capacity to center around real-world context, to understand how individuals and systems adapt towards healthier states. To do this, theoreticians must be able to synthesize and integrate perspectives from a wide range of disciplines that seek to study and measure consumption processes, such as nutrition, behavioral science, ecology, systems science, and engineering. To our knowledge, the theoretician role for consumption processes does not formally exist—particularly one that can fuse multiple disciplinary perspectives to support practical needs and understand methodological and technological opportunities. This paper is meant to provide a starting point for the development of this new role in relation to food consumption processes.

Continuing with the physics analogy, our secondary audience is similar to empirical physicists, which we label "methodologists." We define methodologists as those individuals who build measurement protocols and identify or build technologies in support of those protocols. We broadly define this secondary audience of methodologists to include those with expertise in areas such as measurement and study design as well as technologists in areas such as user experience design and engineering. For the purposes of this paper, a tertiary audience is practitioners, defined as the end benefactors of work produced by food consumption theoreticians and methodologists, including the tools produced for measuring consumption processes. Based on this definition, we include in this group clinicians and interventionists, as well as others who measure consumption to study or effect change in consumption processes, such as epidemiologists. Given the ultimate pragmatic goal of advancing individual, societal, and planetary health via improving food consumption processes, theoreticians need to be able to integrate the motivations, needs, and perspectives of practitioners into their conceptualizations.

Figure 1 illustrates how these 3 audiences interface with the consumption process framework—the focus of this paper—as well as subsequent development of measurement protocols and technologies informed by the framework. The "double-diamond" backdrop is adopted from the UK

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Address correspondence to JCT (e-mail: jtaylor@eng.ucsd.edu).

TABLE 1 Elements comprising the consumption process framework

Element	Key Questions
1) Co-interacting systems Dimensions: • Boundary specification of systems • System interactions	*1A*) Why study consumption—what desired state(s) does this work towards in context? *1B*) What processes seem to produce the desired state(s) in context? More specifically: • What is the focal system? (Which process is of focal interest and where does this occur?) • What subsystem(s) within the focal system must be specified to properly understand the focal system? (What underlying mechanisms shape this process?) • What surrounding system(s) is the focal system adapting to as its broader context?
2) Time Dimensions: • Timescales • Dynamics	*2A*) What timescales most meaningfully describe this process? What are short- and long-term timescales for this process, and how do they relate? *2B*) How does the process unfold dynamically within and across these timescales? Consider continuity (does the process change occur gradually or abruptly?), regularity (does the frequency of change repeat in a predictable manner such as a cyclical pattern?), and intensity (is the change of a relatively small or large magnitude?)
3) Consumption characteristics Dimensions: • What food is eaten and how food is eaten • Quantity and quality • Absolute and relative • Physical reality and social reality	What about the act of consumption is most relevant to the process? What consumption characteristics must be specified to adequately address consumption's role in key process(es)? In this process, is consumption focused on what foods are eaten or how foods are eaten? Is this better characterized as some measurement of quantity or a characteristic of quality? Are these definitions absolute or relative to something else? Do the constructs of interest follow a physical reality based on a common standard, or on social reality based on how a person or group perceive consumption?

Design Council (17) to illustrate how these roles support iteratively moving between conceptualizing the consumption process (discovering and defining these phenomena) and operationalizing that process to support measurement (developing and delivering protocols and tools to measure those phenomena). While this paper is most heavily focused on supporting theoreticians in the conceptualization of consumption processes, we also describe how the practitioner and methodologist roles are integral to that effort—with practitioners being critical collaborators to discover and define consumption processes of interest based on practical needs and methodologists equipped with the skills and resources to move from conceptualization to operationalization with development of measurement protocols and technologies.

The following sections *1*) provide a justification on the need for such a framework; *2*) introduce the consumption process framework, including defining terms and its elements for elucidating complex consumption processes; *3*) illustrate the framework via a use case, with a particular focus on unpacking consumption process complexities; and *4*) discuss implications for measurement protocols, including considerations of how existing technologies could support use of the framework towards this effect and, by extension, more rigorous study of consumption.

The Consumption Process Framework

Table 1 is a summary of the consumption process framework, which is a series of questions to support specification of 3 elements—co-interacting systems, time, and consumption characteristics—including offering dimensions to support defining each. Central to all of this work is a high-level assumption: adaptation is the norm, not the exception. By this, we are recognizing the importance of thinking in explicitly evolutionary terms whereby the actions of organisms take place in context, over time, and involve adaptations that support, at the most basic level, survival, with extensions possible, such as moving towards health, thriving, and reciprocity (18). **Figures 2–4** provide visualizations one could use when answering the questions as part of the framework. We embed "consumption characteristics" as an element of the consumption process framework to emphasize that definitions of "what" and "how" food is consumed in context are meaningful only to the extent they address "why" food consumption is studied as part of some underlying process in context, which we describe based on systems and time. Through this, assumptions about how a consumption process occurs are made explicit, which can then guide measurement protocol creation. In this section, we define terms used and unpack and provide justification to each of the core questions of the framework.

Co-interacting systems.

A system can be thought of as some facet of the universe that contains processes, contained by some boundary, and which interacts with other bounded systems. For example, a cell represents a bounded facet of the universe where dynamic processes take place, with a semi-permeable membrane that allows only some resources to flow in and out. A boundary can be observable, such as a cell membrane, or

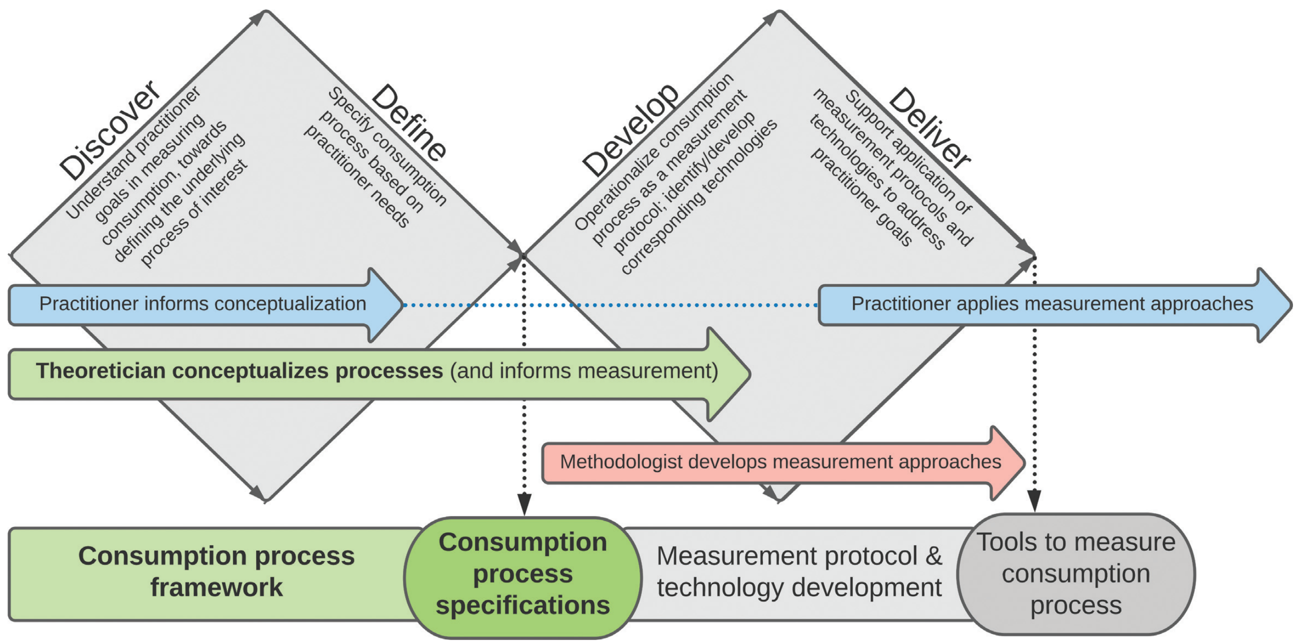

FIGURE 1 The consumption process framework, and subsequent development of measurement protocols, illustrated as it applies to 3 audiences. Theoreticians are defined by their role in supporting clear specification of consumption processes, to serve as a bridge between the measurement needs expressed by practitioners (e.g., clinicians, behavioral interventionists) and the capacities of methodologists (including designers, engineers) to build measurement protocols and technologies. The double-diamond background is adopted from the UK Design Council (17) to illustrate how these audiences could work together—iteratively moving between discovering and defining consumption processes (first diamond, as focus of this paper) and developing and delivering measurement approaches based on those definitions (second diamond). In this way, conceptualizations of consumption processes inform measurement protocols and technologies, and those measurement approaches can then inform further discovery and (re)defining of process conceptualizations.

imagined and socially constructed, such as a family, city, or ecosystem. A boundary, in a systems formulation, fulfills the need for categories that distinguish what is and is not of focal interest. Co-interacting systems implies there are multiple systems that dynamically influence one another in some way, such that a *focal system* specifies process(es) of interest to work toward a desired state, while *subsystems* nested within the focal system describe underlying processes necessary to understand the focal system. A focal system also interacts with *surrounding and adjacent systems*, which serve either as context or as a parallel process, particularly as a possible broader context to which the focal system adapts (19).

Boundary specification of systems defines the focal system, based on the desired state(s) we are working towards, as well as sub-, surrounding, and adjacent system(s), based on the processes that change the state of that focal system and, by extension, contexts of adaptation. Setting boundaries to define relevant systems, including specifying how these interact, serves to answer the question, "Why study consumption?" on the basis of values, intents, and desired future states. More specifically, a theoretician might ask, "What desired state(s) does this work towards in context?" Thus, the intent of the person/group studying consumption processes is accounted for in the specification on what is focal, compared with what might be sub-, surrounding, or adjacent systems. For example, 1 discipline may treat a cell as the focal system, with organs or the human body as plausible surrounding systems and mitochondria and nuclei within cells as subsystems. Another discipline may treat the human body as the focal system, with the surrounding system being the family eating environment, and organs as subsystems. Thus, 1 person's focal "system" is another person's surrounding system, adjacent system, or subsystem, contingent upon the higher-order "why" motivations. And, depending on intent, the boundaries created for defining a system might be readily transferable to another intent or the boundary may be problematic. For example, the notion of the "limbic system" as the site within the brain that controls emotion is contested as not only poorly matched to evolving evidence from neuroscience but also creates a problematic understanding of emotions (20). We use the term "co-interacting systems" to connote both of these properties—that systems function dynamically with other systems, and that the boundaries defining systems must always be remembered as fluid since they are established based on the intentions and beliefs of the person defining their boundaries.

System interactions describe the ways in which consumption processes occur within and between systems, such that consumption can influence, or be influenced by, changes to the state of each system. For instance, one

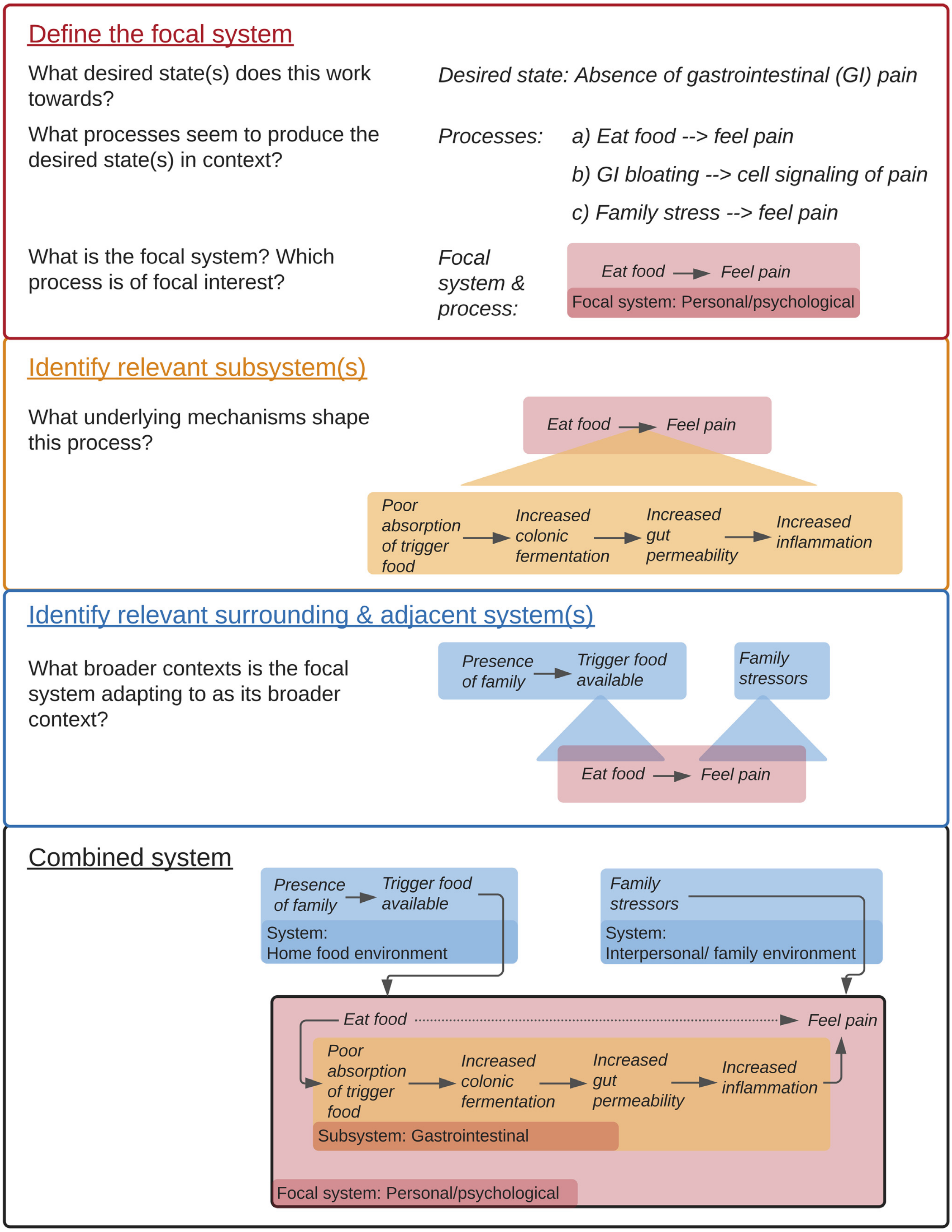

FIGURE 2 Co-interacting systems applied to a food consumption process. Using the example scenario for Roma of navigating food choices impacting gastrointestinal symptoms, this graphic illustrates how system boundaries and interactions are specified. The focal system is first identified based on the desired state that Roma is working towards, as process(es) in this context. Subsystems describe underlying mechanisms nested within that process, while surrounding and adjacent systems describe external influences that affect this process.

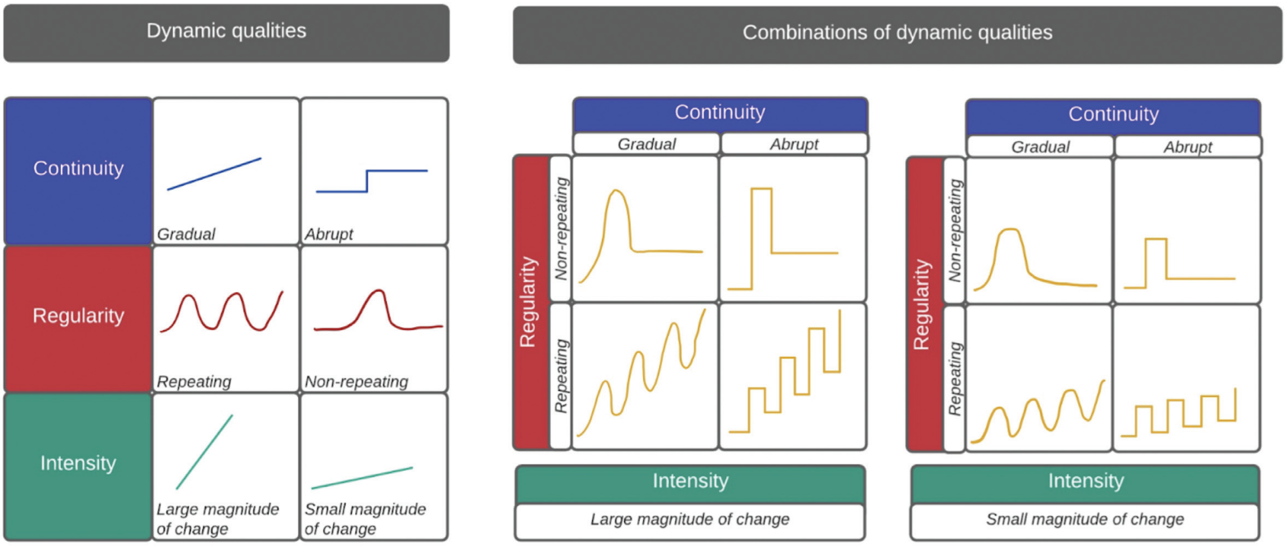

FIGURE 3 Dynamic qualities describing consumption processes over time. Dynamic qualities are illustrated individually on the left for *continuity* (does the change occur incrementally/gradually or discontinuously/abruptly?), *regularity* (does the frequency of change repeat in a predictable manner such as a cyclical pattern or in some sort of wave form?), and *intensity* (does the change vary in magnitude, for example "spiraling" such that there is an accelerating rate to a cyclical pattern?), and illustrations on the right show how these 3 qualities can be combined.

could study how the foods a person consumes shape the composition of the gut microbiome within the digestive system. In this case, the person's behaviors (e.g., what foods are consumed, including food-preparation behaviors) serve as the surrounding system to which the focal system (digestive system) is adapting to. The focal system could also be explored in more depth by examining subsystem changes in gut microbiome function—for example, based on changes in food metabolism or the abundance of certain bacterial strains. In other cases, the person's social connections may be the surrounding system at which adaptation occurs, as when a person adjusts what and how much he eats in the presence of a coworker. Figure 2 illustrates an example of co-interacting systems, which is discussed in more detail with the example use case in the next section.

Time

When consumption is approached as part of a process, timescales and dynamics must be taken into consideration. *Timescales* aggregate time to separate a present moment from some past or future frame, with these intervals represented by clock time such as minutes and days, as well as personally defined experiences of time such as "lunch" (21, 22). Timescales, like systems, can be collapsible, such as minutes folding into hours and lunches folding into meal routines, such that dynamic processes examined at 1 timescale can be aggregated into a more macro scale (23, 24). As any 1 timescale presents a limited understanding of a phenomenon, multiple timescales, including linkages between timescales, may need to be considered for a complete picture. Timescales invite one to think more about the duration of a phenomenon, in the terms that make sense for that phenomenon—such as natural rhythms of seasons impacting food availability—instead of being bound to notions of time linked only with clocks or with the conventions of a measurement protocol. The appropriate timescales to study a given phenomenon depend on how frequently it occurs and can change over time. [Linking more to measurement, timescale can also be conceptualized in terms of the Nyquist Frequency as used in signal processing (25), which postulates that, to study a phenomenon, one must sample at a rate that is twice the speed of the inherent dynamics of the phenomenon, thus enabling those dynamics to be detected.]

Dynamics describe the ways in which a process occurs over time, moving through periods of relative stability (steady states) and change. As 1 orientation to this, George and Jones (21) suggest considering what, how, and why constructs unfold over time on the basis of temporal qualities, such as how time is subjectively experienced and aggregated, how a construct shifts between periods of steady states and change, and the nature of that change. In addition to these considerations, dynamic orientations can specify the nature of cause-and-effect relationships, such as the nature of lags or latency between action and outcome (26, 27). Building on these orientations, we emphasize 3 attributes of dynamics characterizing change that we contend are particularly informative in relation to consumption (see Figure 3): *continuity* (does the change occur incrementally/gradually or discontinuously/abruptly?), *regularity* (does the frequency of change repeat in a predictable manner such as a cyclical

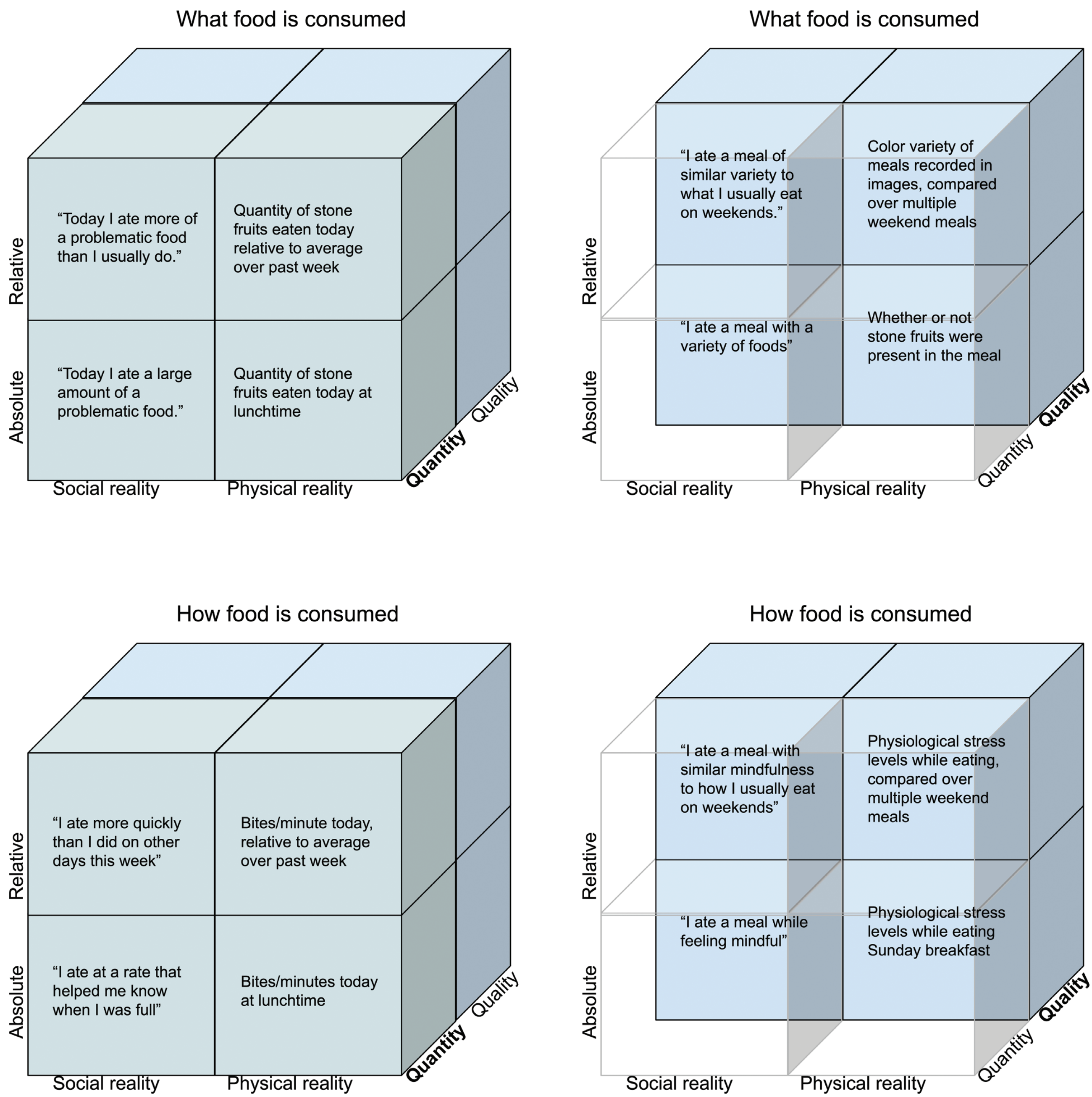

FIGURE 4 Example combinations of dimensions characterizing food consumption. Food consumption can be characterized across multiple dimensions, with the following graphics providing examples based on 4 dimensions considered in the paper: what and how foods are consumed, quantity and quality, relative and absolute, and social reality and physical reality.

pattern or in some sort of wave form?), and *intensity* (does the change vary in magnitude, e.g., "spiraling" such that there is an accelerating rate to a cyclical pattern?). These qualities can be combined to consider the nature of a consumption-related process as shown in Figure 3. For example, coffee consumption for a person who drinks 1 cup every morning would exhibit a daily repeating pattern (regularity) in which an hourly timescale would show an abrupt (continuity) rise and fall in consumption early in the day, reflecting similar quantity consumed each day during these peaks (intensity). If this same consumption process were observed at a more micro timescale such as minutes, a more gradual change would be observed, underscoring the importance of specifying timescales.

Consumption characteristics embedded in consumption processes

There are myriad ways to define food consumption. Specifying the nature of this process based on co-interacting systems and time serves to narrow down what aspects of consumption are most meaningful to study. In this section, we describe 4 interacting dimensions for characterizing food consumption that can be combined to define consumption characteristics: what versus how food is consumed, quantity versus quality, absolute versus relative, and physical reality versus social reality. Consumption is often described based on what and how food is eaten, and these 3 additional dimensions were identified based on multiple use cases discussed among the co-authors. We invite researchers to explore other dimensions for defining consumption as these may not be exhaustive, and as other frameworks demonstrate more ways to characterize consumption (28). Interactions between the 4 dimensions addressed below are further illustrated in Figure 4.

These 4 dimensions are most readily described in relationship to one another, but we first briefly summarize each in isolation. *What* is consumed describes the kinds of foods eaten, whereas *how* food is consumed describes the ways in which food is eaten. The *quantity* of food consumption accounts for some numerical aspect, whereas *quality* of food consumption describes some other attribute or categorization. Food consumption can be described in *absolute* terms independent of any comparators or in *relative* terms that draw comparisons. Finally, consumption may be described based on *physical reality*, where there is a common standard or "objective" definition of consumption, or based on *social reality*, where personal or shared perceptions define consumption (20). Specific examples follow based on the ways these dimensions interact.

As a starting point, definitions can account for *what* is consumed in terms of quantity and quality. With respect to quantity, consider how an amount consumed is shaped not only by common units of measurement like grams and calories but also based on culture, subjective experience, and social realities, such as differing concepts of "serving size" within and across cultures. These quantities are often defined in absolute terms based on a specific eating occasion, but they can also be described relatively based on differences across time, context of eating, or culture (as a surrounding system), as when comparing 2 days of intake, or when a person chooses how much to eat by referencing what their dining partners do. To characterize the quality of what is consumed, foods and their component parts can be organized according to multiple classification systems, such as food and nutrient databases (29, 30). Foods can also be characterized based on other motivations, such as their impact on environmental sustainability (31) or gut microbiome composition (32). Ontologies for integrating multiple attributes of foods extend to other areas such as food processing and provenance (33).

Food consumption can also be defined based on *how* food is eaten in terms of quantity, such as speed of eating, or in terms of quality, such as characterizing mindful eating (34). For example, emerging technologies detecting bites and chews can detect when food is eaten as well as the speed of eating (35–37), as when seeking to understand how meal timing impacts metabolic health (38–40). Broader contextual information such as social cues from dining partners can motivate measurement of other qualities, such as mimicry of food consumption (41, 42). Defining how food is eaten could also extend to subjective experiences representing a person's unique perception of an eating occasion as a meal versus a snack (43).

The examples above touch on combinations of these 4 dimensions. The fourth dimension, physical reality versus social reality, is alluded to in describing subjective experiences, as with personal definitions of portion sizes. We briefly expand on this dimension, drawing on neuroscientist/psychologist Feldman Barrett's work (20), to encourage reframing of objective more as fitting in the domain of physical reality concepts and subjective as fitting more into the domain of social reality, with both being equally important. (The term "subjective," particularly in this context of nutritional assessment as advanced within Western cultures, has historically had a good deal of negative connotations. In some instances, these concerns are well grounded, resulting from there being a disconnect between what construct one conceptually wants to study and what measurement is used to operationalize that construct. Specifically, the use of self-report methods, based on subjective forms of measurement, can be problematic when the goal is to measure a construct based on objective conceptualizations of consumption, such as quantity of food consumed defined by standard units of weight or volume. However, this should not negate the value of subjective forms of measurement when the goal is to study constructs focused on a person's or group's unique experiences consuming food.)

Physical reality refers to facets that can be fully understood and studied without the need to account for context, perceptions of an observer, or co-created perceptions as they exist within a sociocultural context. Thus, physical reality conforms to the notion of "objective" phenomena and is the province of scientific areas such as physics, chemistry, and, to some degree, biology. A definition of consumption based on physical reality describes a commonly shared definition or standard, such as the number of kilocalories in 100 g of food. Meanwhile, social realities involve the ways in which humans independently and cooperatively construct perceptions of reality. While social realities are, to some extent, bound to physical reality, they do ultimately function by their own rules co-created between humans (e.g., languages, laws, customs). For example, consumption, as understood as being influenced by one's social reality, recognizes that physical experiences like chewing and consuming certain foods are uniquely interpreted by each person. One person could perceive eating an ant as a nutritious meal, rich in protein, whereas another person may experience a gag reflex from the same physical object to be consumed. Physical and social realities interact. Consider how a snack can be defined in accordance with notions of physical reality, based on physical attributes such as amount of fiber per gram, and defined in accordance with social realities based on expectations of fullness drawing from a person's prior experience with similar foods. Both of these qualities are valid, when for example, studying satiety signaling (44). Thus, the study of consumption requires a careful understanding of physical reality topics, social reality topics, and the ways in which they interact.

In summary, to accommodate the many motivations for measuring food consumption, this framework seeks to make assumptions about systems, time, and consumption as elements defining a consumption process more explicit and intentional.

Consumption Process Framework in Practice

To help make this framework more understandable and usable for others, below we present a scenario illustrating how a theoretician might be able to better specify a food consumption process using this framework, to support a practitioner (in this case, a clinician and their client) address a consumption-related health concern.

Imagine Roma is a woman who, at age 45, experiences gastrointestinal (GI) symptoms (e.g., cramping pains, bloating) several days of the week. In consultation with a clinician, Roma shares that she suspects these are tied to her diet, but, after experiencing similar symptoms for several years, she remains uncertain of what food or foods contribute to the symptoms. She notices a pattern in which symptoms are at their worst in late summer, and her working hypothesis is that it is triggered by seasonally available foods (e.g., she tends to eat more stone fruits like cherries in late summer, relative to other times of year). As a starting point, Roma might be asked to log her food intake and corresponding GI symptoms for a week to examine how they may be interrelated. But would that measurement protocol elucidate the complexities sufficiently to help Roma make more informed decisions about her consumption? What if Roma's symptoms are seasonal, such that they wax and wane over a much longer time span than is captured with a day-to-day log? What if, instead, Roma could examine her food intake and her symptoms through low-burden approaches that enabled monitoring over longer periods—capturing the full range of her experience to start, and then narrowing to the specific days or hours based on the dynamics of her symptoms? Establishing what to focus on as low-burden continuous measurements, time points that would trigger more intensive measurements, and what measures to include during intensive measurement batteries, requires first building a solid working understanding of consumption processes of interest. Theoreticians can apply the consumption process framework to build this prerequisite knowledge, by answering questions pertaining to co-interacting systems, time, and consumption specification aligned with Roma's needs and Roma's and her clinician's working understanding of her issue.

Co-interacting systems

Step 1A. Why study consumption? What desired state(s) does this work towards in context?

In Roma's case, the goal is to support healthy gut functioning and to reduce experiences of GI pain. We are measuring consumption to understand how it may affect these states of the gut, and to do so we first need to discern what system(s) are most appropriate to study processes that could impact Roma's experience of pain. For Roma, there are multiple potential systems of interest—including a digestive system addressing gut function and a person-level system addressing psychological experiences of pain.

For the purposes of this example, we begin with examining the individual psychological experience of pain as the focal system, which requires an understanding of the ways different social realities and physical realities each function and interact. Central to this is a mapping out of plausible physical reality subsystems addressing gut function to meaningfully understand and engage with the phenomenon of interest. With that said, an awareness and documentation of the sociocultural context are also essential to understand the surrounding systems that shape Roma's perceptions and experience of pain.

From this line, pain is defined by the concepts, labels, and meanings Roma uses to make sense of her experience. In particular, building on Feldman Barrett's work (20), Roma's experience of negative arousal is linked to the social concepts from her culture that provide her with a capacity to describe this experience as pain, predict its occurrence, and, hopefully, gain some degree of control over that negative arousal. Figure 2 illustrates these co-interacting systems, including demonstrating how the inputs and outputs for the GI subsystem can describe potential physiological mechanisms that link food consumption and perceptions of pain within the focal system.

Step 1B. What processes seem to produce the desired state(s)? What systems matter to understand that process?

Focusing on Roma's experience of pain, we can create testable hypotheses regarding how food consumption impacts symptoms that link the focal system to other systems. These hypotheses can address subsystem hunches about underlying mechanisms in GI system function, as described above, while surrounding systems may help specify the various contexts shaping the consumption actions and their effects within the focal system. For example, imagine that a theoretician applying this framework explores the nature of family meal dynamics and seasonal food availability (surrounding and adjacent systems) that suggest how food consumption variation over time might correspond with symptoms (focal system). The theoretician might learn this through the practitioner, based on Roma's report on these experiences as well as their clinical intuition, and the theoreticians might also draw on relevant literature. Based on this, the theoretician may decide that Roma's experience of pain is best studied when eating at home, to incorporate pain symptoms before and after meals, changing home food availability, and the presence of other family members. In collaboration with the clinician, a theoretician might also engage in deeper probes on the level of granularity Roma has related to different types of pain/negative arousal (e.g., shooting, dull, aching, warm, discomforting, etc.). Further, based on the model from Feldman Barrett (20), another plausible hypothesis to explore is her awareness of the impact of context (e.g., other people, certain places, times of day, or after other behaviors) that might influence perceptions of pain and judgments about impacts of different foods.

Time

Step 2A. What timescales most meaningfully describe this process?

Roma's social reality of pain and its potential linkages to consumption can be examined across multiple timescales, such as minutes, hours, days, and months, with the latter accounting for seasonal variability in symptoms. Building on relevant systems raised in the previous section, including family meal qualities and home food availability, a theoretician can specify timescales over which these are thought to influence Roma's experiences of pain. This could be based on scientific literature or initial data gathered with Roma's clinician. Timescales can also be iteratively defined—for example, by first monitoring Roma's experiences of pain over hours, days, or weeks, to then specify timescales over which food consumption may interact with changing symptoms.

Imagine that Roma's symptoms follow consumption of polyol-rich foods such as cherries, peaches, and plums—foods she tends to consume in substantially higher quantities in the summertime and which have previously been associated with GI symptoms (45). To discover this, a theoretician might first generate hypotheses based on Roma's report of seasonal symptoms, which would suggest theorizing processes occurring over weeks and months. As data are collected at these timescales (see later section, Building Measurement Protocols from Consumption Process Specifications), this may then direct a theoretician to consider other timescales such as hourly or daily timescales. In this scenario, a theoretician might hypothesize that Roma experiences sustained, gradual increases in symptoms during the summer as exposures to polyol-rich foods increase, but, when consuming these foods sporadically in other seasons, she observes acute, abrupt increases in symptoms with less severity. In approaching consumption as part of dynamic processes in context, the theoretician's conceptualization of this process can support a practitioner in recognizing symptom patterns that are observable only when considering multiple, collapsible time intervals in which food consumption is aggregated, which in this case create distinct representations of "diet." Thus, looking at timescales to guide definitions of consumption processes, it is the slower timescale of the surrounding system of food production that is conceptualized as a key input influencing Roma's consumption behaviors and ultimately symptoms—including subsystem mechanisms addressing digestive functions such as motility and gut permeability.

With that said, another possibility a theoretician might explore, more in the realm of social reality system factors, could be certain people or contexts that inspire Roma's experiences of pain. For example, perhaps Roma does not merely eat more stone fruit over the summer but also has a regular vacation planned with distant relatives she only sees that 1 time per year. In this case, the theoretician might develop an alternative hypothesis where it is not the stone fruit, or at least not entirely; it is Roma's experience of discomfort arising from her pending time with family, which, in this instance, happens to conform with when she also eats stone fruit. And, given her culture, she may underemphasize the influence of this social reality on her pain, searching, instead, for some physical reality explanation, such as stone fruit, to place the blame. Again, this implies timescales for this process such as monthly assessments of Roma's interactions with other people as a plausible signal that might co-interact with her pain.

Step 2B. How does this process unfold dynamically within and across these timescales?

The dynamics of Roma's experiences of pain can be examined within several timescales. For example, within the minute-to-minute timescale, Roma may experience gradual shifts in pain (continuity) over daily cycles that correspond to meal timing (regularity), and with small changes in magnitude (intensity) when observed on a minute-to-minute basis. Meanwhile, when examined at a monthly timescale, experiences of pain may show gradual shifts that rise and fall with seasonal variation in food consumption. Accrued exposure following increased consumption of triggering foods would be expected to correspond with more intense experiences of pain that spiral upward.

By conceptualizing consumption-related phenomena over time and with intervals that capture a meaningful amount of granularity for a given goal (in Roma's case, based on understanding how they correspond with GI symptoms and, now also, with the possibility of increased discomfort in different social contexts), the theoretician could begin to specify the dynamics of these processes to understand potential bidirectional relationships, feedback loops, lags, and other interactions between phenomena. Using lags as an example, consider how Roma's experience of GI cramping might gradually increase over time. Roma may notice deleterious symptoms about an hour after consumption of a food and, based on that, avoid that food. However, if it turns out the symptoms Roma gradually senses follow 6 hours after consumption of the true trigger food, the wrong food may be eliminated due to a misunderstanding of the lag time. Or, if her interoceptive experience of negative arousal is being triggered more by her future predicted concerns of engaging with some family members, but she exists in a culture where such social reality possibilities are not recognized, then she might seek a physical reality explanation (i.e., "it's what I ate") rather than a social reality explanation (i.e., "I need to learn how to better interact with my family"). From the perspective of the client or clinician, the more the effect is lagged from the action, the harder it is to detect this possible relationship. The theoretician's application of this framework can support specifying these dynamic qualities, informing later development of measurement protocols and technologies that can account for a lag over several hours and account for competing hypotheses. This only cursory, but highly plausible, illustration highlights the foundational importance of carefully considering the many aspects of dynamics.

Consumption characteristics

Step 3. Based on the above, what consumption characteristics must be specified to adequately address consumption's role in key processes?

In this final step, the goal is to define what characteristics of food consumption are most relevant to understanding how Roma's food consumption contributes to processes of interest. Building on the previous section, we describe multiple ways this might be specified, using the 4 dimensions described earlier for consumption characteristics.

At first, Roma's food consumption may be characterized based on the occurrence of eating episodes within a certain number of hours before symptoms are experienced. With this initial focus on how food is consumed, these eating episodes could be specified based on a commonly shared definition (i.e., physical reality)—for example, based on chewing patterns (46)—to determine when and how often these eating episodes occur (absolute, quantity). As these potentially triggering eating occasions are identified, consumption might then be specified in terms of what foods are consumed, to characterize the types of foods consumed (quality) and later to assess quantities consumed of food types, such as polyol-rich foods. As there are standardized definitions for this food category, this again would fall in the realm of physical reality. This specification of consumption could be examined in absolute terms, such as quantity consumed of polyol-rich foods within a 3-month summer period, or in relative terms, such as comparing consumption of these foods between periods with lower and higher symptom severity. Surrounding systems, such as changes in food availability over time, could also support iteratively characterizing what types of foods Roma consumed by assessing relative changes in the composition of meals consumed during periods with varied symptom intensity.

The theoretician could also explore how Roma's symptoms relate to experiences of stress, based on hypotheses about how this process of pain may also correspond with the timing of stressors, such as seeing distant family members during a summer vacation. In addition to studying how states of stress as a surrounding system directly influence experiences of pain (see Figure 2), these family stressors could also be studied as influencing how food is consumed—for example, by characterizing emotional eating behaviors or mindful eating (quality)—making comparisons (relative) between periods with lower or higher symptom severity. These qualities characterizing how food is consumed could specify consumption as a physical reality, such as characterizing physiological stress responses while eating, or as a social reality—for example, if Roma were to self-reflect on her emotional state and ability to eat mindfully after a particular eating episode.

In summary, for Roma, consumption processes are iteratively defined and could gradually be narrowed to specify consumption characteristics based on surrounding system influences such as foods available when with family as well as alternative hypotheses around social dynamics. Subsystem assessments of GI function could also discern underlying mechanisms by which consumption impacts pain. While a priori definitions of consumption characteristics might be feasible in other scenarios, this example illustrates how a consumption process framework allows for emergent definitions that can be used to guide consumption process specification, and subsequent measurement development, and to be more aware of the potential unintended consequences and tradeoffs of alternative definitions.

This hypothetical scenario illustrates how the consumption process framework can be used to guide the study of relationships between food consumption and health, including enabling subsequent efforts to strengthen measurement based on process specifications generated through this framework. In addition to Roma's scenario, the framework described above and summarized in Table 1 could be applied to other food consumption processes. For example, how might a behavioral scientist design an intervention that could support a person with type 2 diabetes to monitor and adapt to his unique metabolic phenotype? This practitioner may want to understand how a person's blood glucose regulation could be managed through changes in the timing of eating occasions and fasting. To study this, a theoretician could support this practitioner to define how these facets interact with other aspects shaping meal timing and nutrient metabolism, such as sleep patterns, with the goal of optimizing blood glucose concentrations or other outcomes that matter to the person receiving that intervention. As another example, how might a public health practitioner such as an epidemiologist examine population-level changes in food security in a neighborhood impacted by an economic recession? A theoretician applying this framework could support a practitioner in defining processes that account for changes in neighborhood wealth and purchasing behaviors, towards improving food security and other states related to quality of life. Each of these examples conveys unique needs for those seeking to measure food consumption processes, calling for different process specifications to be conceptualized. **Table 2** summarizes the use case for Roma and also applies the framework to these 2 examples to further illustrate its application.

TABLE 2 Application of the consumption process framework to 3 scenarios[1]

	Case Study Examples		
	Example 1	Example 2	Example 3
Summary of practitioner goals	A clinician wants to support a woman in understanding how the foods she eats (what foods, when) may contribute to GI symptoms	A behavioral scientist wants to design an intervention that helps a person with type 2 diabetes to manage blood glucose through food choices and meal timing	A public health practitioner wants to monitor neighborhood-level food security during an economic recession
Element of consumption process			
Co-interacting systems	Desired state based on GI pain: Focal system process: person's experience of pain (to examine how unknown food consumption may contribute to GI pain) Subsystem(s) of interest: digestive system (e.g., potential roles of food consumption on gut permeability and inflammation pathways) Surrounding and adjacent system(s) of interest: person's food availability and interpersonal environments (e.g., how presence of family shapes foods available from meal to meal, as well as experiences of pain)	Desired state based on variation in blood glucose, as part of diabetes management: Focal system process: endocrine system function (to examine how food combinations consumed and meal timing affect blood glucose patterns) Subsystem(s) of interest: organ and cellular level changes in metabolic pathways (e.g., changes in concentration of glucose, cell turnover supported by increased autophagy) Surrounding and adjacent system(s) of interest: sociocultural structures shaping timing of eating, sleep, and other schedules	Desired state based on neighborhood-level measures of food security: Focal system process: changes in neighborhood wealth and purchasing behaviors (to examine how wealth and purchasing behaviors impact what and how much is consumed by households, including skipping meals) Subsystem(s) of interest: household-level changes in income and work patterns (e.g., getting a second job) influencing household food purchases and meal routines that ultimately impact food consumption Surrounding and adjacent system(s) of interest: economic patterns affecting job stability, food prices, neighborhood living costs
Time: timescales and dynamics	Short-term: minute to minute and hourly lags between potentially triggering eating episodes and pain experiences Long-term: seasonal patterns in symptom intensity potentially attributed to accrued exposure to triggering foods	Short-term: minute to minute changes in blood glucose concentrations in response to specific foods or food combinations Long-term: month to month changes in magnitude of blood glucose cycles in response to changes in meal timing	Short-term: weekly changes in neighborhood food purchases from nearby food venues and weekly changes in household-level food security Long-term: year to year changes in adverse childhood experiences connected to food security; year to year changes in neighborhood cost of living and quality of life
Consumption characteristics (focused on quantity and quality)	Quality: specific foods or food components linked to timing of pain experiences Quantity: relative quantity consumed of suspect food, compared to other days or seasons; frequency of consumption of triggering food	Quantity: relative quantity consumed of food between periods of feeding and caloric restriction (or fasting) Quality: food types and combinations consumed, characterized based on their effects on blood glucose	Quantity: relative quantity of neighborhood food purchases, absolute change in frequency of meal-skipping Quality: types of foods purchased in terms of energy, nutrient density per dollar, and cultural appropriateness to the family

[1]GI, gastrointestinal.

Building Measurement Protocols from Consumption Process Specifications

The focus of this framework is on elucidating the complexities of a consumption process, as a precursor to developing measurement protocols (Figure 1). While a fully fleshed out explanation of measurement protocols is beyond the scope of this paper, we briefly describe how measurement protocols could be supported based on the outputs of this framework, which would be the activities of our secondary audience, methodologists. At this stage, the theoretician's goal is to support methodologists in building out a measurement protocol that is informed by identified systems and corresponding timescales and dynamics relevant for each, such that consumption phenomena are studied not in isolation but as part of processes most meaningful to the practitioners who will use them.

To illustrate with Roma's story, measurements could be quite crude at first, aiming to determine dynamics connecting how food is eaten and GI symptoms. For example, passive sensors detecting hand-to-mouth movements or chewing sounds might be used at first to determine the timing of eating occasions (35, 36). Roma's GI symptoms might be captured by self-monitoring [e.g., use of ecological momentary assessment to report on symptoms throughout the day in real time (47, 48)] and sensing methods [e.g., gastric contractions sensed through a band worn on the abdomen (49)]. This could also be coupled with a monitoring of Roma's interactions with family members, as could be gleaned from her calendar data (assuming she uses a digital calendar) and further examined, where appropriate, using probing questions (e.g., "Your calendar suggests you went to X; who were you with?").

As patterns of symptoms are determined within a day and across several days or months, these could be examined against the timing and environment of eating occasions, including triggering more intensive measurements of what food is consumed based on correspondence between timing of symptoms and eating. These more detailed assessments might include existing approaches such as image capture of meals (50), which Roma could review independently to uncover commonalities across eating occasions, or with a clinician who helps probe what was eaten. Other forms of monitoring might capture the context (surrounding system) of these eating occasions, such as what foods are available at home versus work, whether eating with family or alone, and stress levels.

Examination of these patterns can inform the design of supports (e.g., clinician consultation, behavioral interventions) for a person like Roma by examining these dynamic interactions in her specific context. Roma may attend to proximal outcomes that change more rapidly—namely, her GI symptoms—with the goal of understanding feedback loops between which foods are eaten and the onset and severity of symptoms. Self-study of her data may inspire relatively simple solutions to be gleaned and enacted (e.g., avoiding specific foods, managing stressors associated with family gatherings). However, it may be difficult for Roma to "see" patterns in her data and engage in appropriate self-experiments to unpack these complexities. With support from a clinician trained in understanding the underlying physiological and psychological systems that influence and are influenced by food consumption, the clinician and Roma could together postulate more complex but feasible patterns.

The addition of sensors, such as a sensor for GI motility, could help with understanding the window from cause to effect as a subsystem. The nature of this interaction between diet and GI symptoms may also be characterized based on the kind of change—perhaps the onset of cramping symptoms occurs gradually for Roma, while bloating may follow a discontinuous pattern experienced as an abrupt change. Sensing technologies may be especially helpful to detect outcomes that change more gradually and are thus less noticeable by Roma, underscoring the value of understanding the relationship between food consumption and pain across these different system levels. Further, working through these questions helps to highlight assumptions and, thus, provide one developing a measurement protocol with a way to think carefully through tradeoffs. What is lost when increasing or decreasing the frequency of assessments? What plausible hypothetical drivers might be missed? Are there ways to get a rougher, but more continuous signal that can be used to get at facets of Roma's experience of pain? With all these competing possibilities in mind, theoreticians and methodologists can together devise a measurement protocol that balances the tradeoffs and, perhaps more importantly, recognizes the likely limitations in their measurement protocol.

While this provides an illustration of what could be, it does not provide an exhaustive account of what we know. For example, other causes of Roma's GI disturbances would need to be considered beyond food consumption. This scenario presents only a handful of potential measurements relevant to Roma's experience, when several other biomarkers, sensing technologies, and tools might be considered here to reflect the state of the art in medicine and technology. Thus, in this example, we did not fully produce a measurement protocol as getting to that level of detail is beyond what can be summarized here. Putting these kinds of caveats aside, this example suggests some of the ways in which the measurement of food consumption might evolve to better account for the ways in which relationships between food and health unfold over time, in contrast to relatively static representations of experiences of food intake within a chronic health condition.

Rethinking Technologies

As Roma's example and other examples we offer throughout this piece illustrate, there are many ways to specify and study food consumption processes. Based on this, there may never be a single technology that addresses all meanings of food consumption. Whether describing a traditional tool such as a paper-based food-frequency questionnaire or an emerging digital tool such as a wearable device passively capturing motions, these technologies for measuring food consumption each bring opportunities and limitations, depending on the consumption process of interest. When the study of a food consumption process begins with determining what technology to use, there is an inherent risk that the phenomena to be studied will be driven by the constraints of that tool, rather than the underlying goals and assumptions of those using the tool. Rather than defining consumption based on the tools at hand, this consumption process framework illustrates how assumptions about a process can be established as a foundation for leveraging (existing and new) technologies.

What if, rather than seeking to collect several somewhat detailed assessments on food consumption across a day or week, as is often the case with dietary recalls and food records, we had a way to balance very cursory scans of consumption over longer periods, with intensely detailed accounts of consumption over shorter periods like a single meal or 10 minutes of the day? Imagine if we could request such intensive data for specific occasions as needed. Scans of food consumption that occur over long periods of time would focus on passively sensed or easy-to-capture aspects that correspond loosely with diet, such as the color composition of foods captured in images of meals (51), or the typical duration of eating occasions as detected through hand-to-mouth gestures (35, 36). Ecological momentary assessments (EMAs), including micro-EMA approaches, could be deployed for brief assessments completed in a matter of seconds, using approaches that are already showing promise in behavioral interventions (52–55). These scans may also passively collect information on system surroundings shaping consumption, such as detecting refrigerator or pantry contents over time using Internet of Things capabilities (56, 57).

These examples illustrate some of the ways methods and technologies, many of which already exist, can approach consumption as a process accounting for relevant information on context and time. Multiple disciplines can inform this endeavor. Increasingly robust approaches to examine linkages between food consumption and health outcomes are in development within the nutritional sciences, such as the growing adoption of continuous glucose monitors alongside improved modeling approaches, towards precision nutrition (58–60). Methodological advances in the behavioral and social sciences are enabling researchers to better manage the complexity of health behaviors that change with context and time (61, 62). Visualization tools and co-design practices drawn from human–computer interaction can support conceptualization of meaningful timescales, including those defined through personal health experiences (63); this orientation could be extended, for example, to understand health effects of "chrono-nutrition" based not only on eating occasions but also based on a person's definitions of "meals" and "snacks" across periods of hunger and satiety (40, 64). All of these opportunities, however, require a careful delineation of assumptions being made about focal consumption processes, hence the need for the consumption process framework. From a technical standpoint, the effective development and integration of technologies such as these is no easy feat. In focusing on how theoreticians can define consumption processes, the intent of this framework is to support measurement protocol and technology development aligned with what is most meaningful to study to a practitioner and methodologist. While supporting greater specificity in defining consumption-related phenomena can be useful to guide selection of existing and creation of new measurement tools, we acknowledge the need for, and invite further exploration of, ways measurement protocols could be developed to best bridge these inputs from theoreticians and practitioners with the technical and resource constraints faced by methodologists.

Discussion

In presenting this food consumption process framework, we demonstrate how assumptions about systems, time, and consumption can be made more explicit to facilitate production of more robust measurement protocols related to consumption as a complex adaptive system. By focusing on potential roles for theoreticians, we invite diverse and coordinated approaches to defining, measuring, and studying what, how, and why food is eaten across efforts. Common dietary assessment approaches such as food records and dietary recalls are often the starting point for practitioners and methodologists interested in the measurement of these processes. These approaches are useful in certain scenarios, depending on the goals for measuring a particular process. However, using these common approaches as a reference point can also create a mismatch between the complexity of what one intends to study and the finite capabilities of any existing method. Thus, rather than starting from a limited set of configurations for systems, time, and consumption, as are implied with common dietary assessment methods (and any existing approach to measurement), this framework invites one to begin by articulating assumptions about a consumption process—undergirded with a complex adaptive systems orientation—and then use those assumptions to guide measurement protocol generation and application by methodologists and practitioners, respectively, with theoreticians remaining connected and actively involved with refining conceptualizations. In this way, and as is illustrated with questions in Table 1, the goal is to first ask, "Why measure consumption?" well ahead of exploring methodological questions such as "What does 'food consumption' operationally mean in this scenario?" and ultimately "How can I measure it?"

By being more specific about systems of interest and their relationships, how might we enable better communication and connection of diverse disciplines studying consumption spanning molecular, clinical, behavioral, agricultural, cultural, and other areas? This consumption process framework demonstrates how success criteria from different disciplines can be integrated when the notion of co-interacting systems is used to specify how processes occur in nested and neighboring systems adapting towards desired states, such as physical, social, and emotional states in context for individuals, societies, and the planet as an extension of the WHO's definition of health (65). By shifting from strictly static and stable notions of food consumption to studying processes that vary over time with unique dynamics, how might we draw on capabilities and tools from disciplines already adopting complex adaptive systems orientations, such as systems science? Finally, how might we advance measurement of consumption by shifting from seeking to capture every aspect of food consumption, to instead seeking to build a range of tools and methods that can be applied in different combinations dependent on the co-interacting systems and their dynamics? The inclusion of multiple dimensions defining consumption in this framework, and the placement of consumption characteristics as the final component of this framework, invites broadened definitions of "what we eat" and "how we eat" at the same time that it meaningfully constrains definitions based on "why" consumption is important within a process based on envisioned states of health for individuals, societies, and the planet.

Aligning with the NIH Nutrition Roadmap's call for more comprehensive and integrated strategies for dietary data capture and analysis (64), the considerations outlined in this framework reinforce the importance of using multiple data-capture methods addressing different dimensions of what and how we eat—working to integrate those data streams to create a multidimensional picture of complex concepts such as "diet." Strategies for integrating multiple technologies and data streams (66), combined with frameworks supporting thinking about co-interacting systems (67), can bring together divergent approaches to studying food consumption. Above all, this framework calls for a shift in how we think about food consumption, from the current tendency to define food consumption in isolation, with an overemphasis on defining "what" and "how" food is eaten, to conceptualizing these phenomena as adaptive processes that gain meaning when defined in the context of systems and time.

In order to support these broadened ways of thinking about food consumption, there is a need for further exploration of how theoreticians can be supported in applying and refining this framework, recognizing that this requires unique capacities to integrate multiple disciplinary perspectives with a complex adaptive systems and dynamics orientation. This is complementary but distinct from building new methods and technologies (i.e., the role of methodologists), and also separate from the application of those tools (the role of practitioners). Because these unique roles of a theoretician are only possible through collaboration with practitioners and methodologists, there is not only a need to support theoretician capacities but also to support collaboration across these 3 roles. These kinds of collaborations are currently uncommon; a dietitian supporting clients (practitioner) may not regularly interface with a researcher who thinks more conceptually (theoretician), and neither may be familiar with the current state of technologies to measure these processes (as a methodologist). For this framework and subsequent development of measurement approaches to be realized, barriers and facilitators to collaboration will need to be addressed. Some existing models of collaboration may also offer examples of how to bridge these roles, such as learning from clinical and translational research centers that bring together applied researchers working on concrete projects as practitioners with those trained in systems science directed towards conceptualization as theoreticians. The consumption process framework introduced in this paper invites a shift in how we fundamentally define food consumption processes and, with that, guides development of more rigorous measurement protocols and corresponding technologies, which would enable us to more effectively study what, how, and why we eat for advancing the health of individuals, communities, and our planet.

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