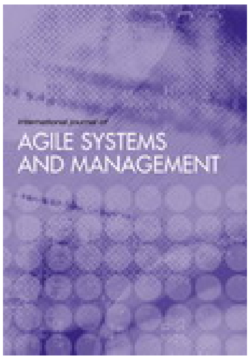

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Ysanne Yeo, Masahiro Niitsuma

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Proposal of an integral model of human-food interaction: insights for social systems design

Ysanne Yeo* and Masahiro Niitsuma

Graduate School of System Design and Management,
Keio University,
Yokohama, 223-8521, Japan
Email: ysanneyeo@keio.jp
Email: mniitsuma@keio.jp
*Corresponding author

Abstract: Designing social systems conducive to long-term positive outcomes for individuals requires a nuanced yet accurate understanding of humans as intricate systems. Despite a corpus of knowledge on human factors influencing behaviour, these are often studied in separate paradigms, challenging system designers to define complete and precise human requirements for human-environment interactions. Embracing the transdisciplinary nature of human factors, this research integrates these dependencies into a more comprehensive representation of human behaviour in a system model. Utilising a model-based systems approach, the paper proposes and validates a system model of human-food interaction in modern society. The visualisation exposes how current 'behaviour change' solutions may be dulling our interoceptive sensitivity across the human lifecycle in favour of increasingly accessible external motivators of behaviour. This research advocates for human needs and highlights potential pitfalls of systemic assumptions of behavioural design approaches, contributing to more informed development of sustainable social systems.

Keywords: human behaviour; human intelligence; human-environment interaction; transdisciplinary research; social systems; model-based systems approach; systems theory.

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Biographical notes: Ysanne Yeo is a design practitioner and researcher. She currently works with the University of Tokyo DLX Design Lab and will complete her Master's degree at Keio University Graduate School of System Design and Management in September 2024. Prior to pursuing further studies in Japan, she obtained her Bachelor with Honours degree in Industrial Design from the National University of Singapore and served as a pioneer in-house designer for the Economic Development Board of Singapore. She sees connections beyond the surface and is passionate about creating spaces of contemplation that bring forth human needs for behavioural resilience and wellbeing.

Masahiro Niitsuma is an Associate Professor at Keio University, Graduate School of System Design and Management. Before taking up his current position in April 2021, he was an Assistant Professor at Ritsumeikan University, College of Information Science and Engineering, and a Lecturer at

Aomori University in the Department of Software and Information Science. He obtained his Doctoral degree at Queen's University Belfast on research focusing on AI-related studies of J.S. Bach. His is interested in the utilisation of AI towards the transmission of traditional Japanese wisdom, believing that the transmission of its essence is a key challenge of our generation.

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1 Introduction

Recognising the inherent diversity within our shared human species, the pursuit of a universal solution for global social challenges seems elusive, especially considering the ongoing discussions on design for subjective well-being (Grover, 2014; Desmet and Pohlmeyer, n.d.). Despite this backdrop, we continue to observe solutions for human behaviour being developed with seemingly contradictory intentions dictating how people should behave, such as using descriptive and injunctive social norms to appeal to individuals to change their behaviour (Herman et al., 2019; Burchell et al., 2013). The behavioural campaigns and information architecture of modern society often prescribe choices that individuals should make, and arguably more so in recent years with technology being able to make decisions in human stead (Wang et al., 2022). While technological convenience allows for passivity and unconscious behaviour, to assume that these systems prioritise our subjective well-being is precarious.

There exists a competition for consumer attention in modern society driven by economic outcomes which may or may not align with subjective human needs for well-being. Both system designers and users therefore share the responsibility of being cognisant of and managing the risks and trade-offs inherent in systemic interactions between humans and our environment to avert unintended negative consequences. Despite the prevailing trend towards extrinsic behaviours in contemporary society, the consequent trade-offs of dependency on external information on the human lifecycle remain insufficiently seen and elaborated.

It is difficult, possibly impossible, to measure impact of (mis)information on behaviour in the real world, with existing data supporting correlation rather than causation, but we do know that humans are predisposed to hold certain beliefs based on our prevailing mental models (Altay et al., 2023). Therefore, instead of focusing on cognitive biases and trying to discern 'truth' from 'falsity' in information itself, this research posits that increasing dependency on extrinsic information itself as a driver of behaviour could compromise innate human sensibilities – which includes interoceptive sensitivity to one's embodied knowledge that helps us to discern and respond appropriately to our bodily needs (Herbert et al., 2013). Based on this premise, this paper proposes an integral view of human behaviour using a model-based systems approach. The system model aims to externalise the internal structures underlying human behaviour in the context of human-food interaction to provide a basis for alignment on the human model underlying social systems design. The model facilitates deeper discussions on the gaps in human assumptions and requirements for human-environment interactions, which prompts the reframing of the problem and solution scope of social systems design.

1.1 Research scope

While this research aspires to describe the collection of mechanisms pertaining to human behaviour, it leverages the context of human-food interaction to crystallise our understanding of how humans interact with environmental stimuli using more relatable and concrete instances. The absence of a universal diet that can ensure subjective health and well-being sets the stage for a model that could represent the complexities inherent in the human system. Interactions with food extend beyond personal taste and preference or hunger. A study on the many meanings of food finds that "Food choice is a product of our cognitions, of familiarity and of our expectations and experiences"; these processes "provide us with a rich set of meanings about food relating to our emotional states, conflict, our social interactions and health" which influence what we eat, how we eat, and how we feel about food (Ogden, 2008). The question then arises: if these meanings are shared by the majority, why do the minority of people still develop eating-related problems? What are the recurring internal processes that could account for unsustainable eating behaviours? Previous studies on complex social-ecological systems have identified 'adaptability' and 'resilience' as essential characteristics of sustainable human-environment systems (Folke, 2006; Smit et al., 2000; Smit and Wandel, 2006; Berkes et al., 2003; Adger, 2000), but as it appears, translating these concepts into practical application requires bridging abstract concepts with structural human requirements for social systems design. We propose that a system model could be used to bridge this gap.

1.2 Model-based systems approach

This paper utilises a model-based systems approach to facilitate the integration of human factors as structures and functions underlying human-food interaction and to study their inter-activities and implications. Borrowing from the successful application of systems modelling in technical engineering, this research recognises that the method's inherent structure serves as a universal language to discuss complex systems with minimal ambiguity, including the human system itself. The system context analysis embedded in this approach allows for a nuanced understanding and representation of human behaviour that considers the intricate interplay of situational factors. Moreover, the integrative viewpoints in a model-based systems approach facilitates the development of an integral perspective, enabling researchers to grasp the interconnectedness of elements within the human system. This approach would not only enhance the depth of analysis of the human system as a whole but also contribute to the development of comprehensive solutions tailored to address the multifaceted challenges confronted by designers of social systems and human interactions.

2 Literature review

Facets of human intelligence studied and proposed by different domains have inherent connections and can be integrated to elucidate the system view of a human individual. In this research, we have identified points of linkages across theories in psychology, physiology and embodied knowledge that allude to inherent structures and activities internal to the human system, underlying human-food interaction.

2.1 Theories on cognitive modalities

Theories of cognitive modalities from the field of psychology posit that decision outcomes can be based on mental, emotional, social frameworks of the mind, which could be processed attentively or inattentively by use of cognitive effort to rationalise specific tasks or by relying on mental shortcuts. This phenomenon is primarily explained by the widely acknowledged dual-system theory of Kahneman and Tversky, which describes the existence of two cognitive processes: System 1 and System 2. System 1 is characterised as the "fast", autonomous response system, requiring little to no conscious effort, while System 2 is "slow" and allocates attention to effortful mental activities. System 2 is sometimes said to involve 'cognitive effort' (Kahneman, 2003). At the crux of the dual-system theory is the understanding that a most decisions are made based on *heuristics* (Kahneman and Tversky, 1973; Kahneman et al., 1982). Heuristics are mental shortcuts which humans learn from experience, and we rely on them to make a majority of daily decisions. In this way, most people would be able to navigate familiar roads and traffic signals without much thought.

However, it is important to note that neither cognitive mode is more correct; and that we have yet to land on a definitive information processing model of the human. Kahneman himself acknowledges, "In making predictions and judgements under uncertainty, people do not appear to follow the calculus of chance or the statistical theory of prediction. Instead, they rely on a limited number of heuristics which sometimes yield reasonable judgements and sometimes lead to severe and systematic errors" (Kahneman and Tversky, 1973). The existence of heuristics entails the risk of making systemic judgement errors if these mental shortcuts are based on misjudged experiences or misbeliefs. To mitigate judgement errors, it becomes imperative that system designers acknowledge these inherent cognitive biases and ensure that external systems are designed to encourage the right patterns of behaviour without reinforcing heuristics based on misguided beliefs; all while we process most of our perceived information beyond conscious awareness.

Adding to this complexity, scientists have proposed theories of selective attention that explain how biases are subjective based on the perceived relevance of information to the individual. *Selective attention* refers to the human ability to filter information (Broadbent, 1958; Moray, 1959; Treisman, 1960, 1964). Broadbent's (1958) and Treisman's (1964) bottleneck selection theories posit that humans have limited resource capacity (attention) to process information at any given point in time. Broadbent's theory suggests that some information is ignored due to the inability of the attentional system, while Treisman's proposes an innate capacity of humans to attenuate information that is situationally less relevant, rather than to eliminate unattended stimuli altogether. Treisman's attenuation theory is consistent with the "cocktail party effect". The early selection theories of Broadbent and Treisman's were later challenged by Deutsch and Deutsch (1963) and Norman (1968)'s late selection model. In the late selection model, filtering occurs after all inputs have been analysed unconsciously before humans are aware. The late selection pathway is contingent on how relevant the stimuli is perceived to be at the time, while physical properties of the stimuli influence selective attention. The influence of perceived relevance on behaviour underscores the idea that an individual's human-food interaction system comprises mental models that attenuate information, possibly pre- and post-awareness. This function of mental perception and its filtering activities need to be represented in the system model to visualise the degree to which behavioural outcomes are dependent on an individual's mental perception.

2.2 Theories on psychological nudging

Leveraging the discoveries of heuristics and cognitive biases from psychology, the field of behavioural economics has established nudging as a means to influence behaviour through external stimuli. Various types of nudging exist in our daily environments, including sensory nudging that appeal to human senses, visual nudging pertaining to information, and other social influences of which a large corpus of knowledge exists but will not be detailed in this research. The essence of nudging lies in that it is a form of intervention in choice architecture that utilises systemic biases in human mental models to compel individuals to make certain choices over others (Thaler and Sunstein, 2008). Since there is technically no neutral way to present information and options to users, one might argue that humans are continually being nudged by our environmental choice architecture. Marketers have been able to capitalise on nudging to influence consumer behaviour towards outcomes that are often based on enterprise goals; and at the same time, private and public social policy makers might endeavour to nudge behaviour towards more desirable outcomes in terms of health, environmental sustainability and other social objectives. The central argument for nudging is that it could improve human decisions while most people are unaware (Benartzil et al., 2017; Vandenbroele et al., 2019; Selinger and Whyte, 2011).

The counterargument, however, is that these extrinsic incentivisation of behaviour could backfire by crowding out intrinsic motivations that are essential to producing the desired behaviour in the long run (Gneezy et al., 2011). Although many nudge techniques seem to achieve their intended effects under controlled settings, it uncertain whether they would work outside of the study environment. A meta-analysis of public health nudge interventions revealed that many studies lacked critical reflection on the assumptions about health that were implicit in nudge interventions, the cultural acceptability of nudges, the context-free assumptions of nudging theory, and the implications of these aspects for the public health context (Ledderer et al., 2020). In fact, it has been argued by the field of neuroscience that nudges can infringe or promote autonomy (Felsen and Reiner, 2015) and there is room for discovery on how the brain's anatomy may be altered in response to changes in choice architecture. This tension between extrinsic and intrinsic motivators of behaviour will be exemplified in the human system model. By representing the subjectivity of perception in the human-food interaction model, the integral view of the human system would more accurately represent the possible reasons for real-world behaviour outcomes of nudging. It would describe the longer-term consequences of extrinsic behaviours on the individual; and we have reason to suspect that human behaviour, especially in the long-term, requires trust in the body's innate functions and drivers of behaviour rather than short-term extrinsic motivations.

2.3 Theories on physiological processes

In addition to theories on cognition, the area of physiology provides significant contributions to our understanding of human system functions and behaviour, supporting the notion that behaviour is also the outcome of natural body structures. The human system is constantly adapting to the demands of its environment at a level which we are often unaware where internal processes coordinate themselves. Metabolic signals can modulate the cortico-limbic systems involved in higher brain functions, and the cortico-limbic systems can hijack metabolic effector mechanisms that control energy balance (Zheng et al., 2009). In other words, gut hunger can impede cognitive processes, and cognitive functions such as learning and memory, attention and focus, planning and execution can wield influence over behaviour. This is evidenced by the emergence of food cravings that surface in response to cognitive stimuli rather than gut hunger. In this regard, by synthesising the role of subjective energetic needs with subjective mental models, the human-food interaction system model can represent the idiosyncratic nature of food behaviour as well as the impact of the food environment on internal functions.

Moreover, at a cellular level, the specific set of taste qualities that we each perceive is considered subjective. Human taste receptors, with their common biological functionality of identifying nutrients and triggering hormonal responses to nutrient stimulation, serve to prevent the ingestion of harmful substances. Deeper cellular research finds that taste signals are initially transmitted to brain stems controlling reflexes of acceptance or rejection, before nuclear relay gives rise to conscious taste sensations. This suggests that food-related behaviours can manifest without the need for higher-level cerebral processing (Breslin, 2013; Leventhal, 1959; Steiner, 1973; Grill and Norgren, 1978). Hence, we infer that instinctual acceptance or rejection, of food in this case, is a form of intuitive decision-making in response to individual needs of the human body. This instinctual response will be reflected in the human system model as bodily knowledge.

In more recent studies, the term ‘gut-brain axis’ has been used to denote the entity of bidirectional signalling mechanisms between the brain and the gastrointestinal (GI) tract. The gut-brain axis has been identified as part of a larger interoceptive mechanism that enables coordination between peripheral digestive processes and the overall physical and emotional state of the body (Weltens et al., 2020; Craig, 2002). The majority of these homeostatic afferent signals are unconscious to individuals, with only salient stimuli – like hunger or pain – requiring more acute response to restore homeostasis reaching consciousness. It is precisely these evidence of the inseparable interaction between the body and brain that highlight the importance of seeing human individuals as whole systems in and of themselves, even as we delve into specific studies of its constituents. Researchers posit that any dysfunction of the gut-brain axis may result in aberrant processing and, hence adversely affect intuitive decision making, which may in turn lead to a wide range of functional and inflammatory disorders (Mayer, 2011; Al Omran et al., 2014; Weltens et al., 2018). Accordingly, it would seem that disregarding the bidirectional communication between mind and body and focusing on brain-centred behavioural interventions could hamper the development of individuals’ interoceptive sensitivities required for subjective health maintenance.

Physiology studies support the argument that human individuals have a natural mechanism within themselves that if allowed to function will ensure adequate nutrition and maintenance of a healthy bodyweight (Herbert et al., 2013; Hawks et al., 2005). It has also been suggested that as individuals get in touch with this ‘inner guide’ they are more in tune with their body’s physical needs and eat in a way that supports healthful food choices and eating habits while avoiding overeating, obsessive food consumption and harmful dieting (Schwartz, 1996; Tribole and Resch, 1996). This style of eating, also known as intuitive eating, is supposed to represent adaptive behaviour because it involves trust in the body and its innate capacity to respond to internal physiological needs and eating cues, rather than to rely on diet plans, environmental stimuli and emotional states to inform behaviour (Tribole and Resch, 1996; Carper et al., 2000; Federoff et al., 1997; Polivy and Herman, 1999; Tylka, 2006). Integrating physiology with psychology to analyse human-food interaction would be to see food behaviour as the outcome of interactions between the mind and body.

2.4 Theories on embodied knowledge

Not only is bodily knowledge innate to the human system, but again it is subjective, contingent on an individual's sensitivity to their intuitive knowledge and the embodiment of their intuition. Evidence from physiological studies support the notion of an "inner guide", which raises the question: what are the factors or circumstances that increase an individual's propensity to embody their intuitive knowledge and behave accordingly to their natural mechanisms? This research finds connections between physiological studies and studies on *embodied knowledge*, also referred to as intuitive knowing (Lawrence, 2012) or bodily intelligence (Parviainen, 2010). As an attempt to capture the role of embodied knowledge in guiding behaviour, this paper will refer to bodily-informed behaviour as 'embodied response' of the body.

Studies on embodied knowledge typically investigate how individuals or groups of people, such as designers and athletes, perform intuitive actions and perceive or "know something immediately, without conscious reasoning" (Oxford English Dictionary). The way that dancers perceive and interact with their surroundings is considered an expression of bodily intelligence inseparable from spatial intelligence (Parviainen, 2010). Deciphering bodily intelligence presents a challenge due to its subjective and elusive qualities (Suwa, 2019). Instead of a universal model of embodiment or intuition, studies in this field are laden with anecdotal, descriptive evidence that implies a connection between individuals and their surroundings. Freiler (2008) defined the somatic learning process as "learning directly experienced through bodily awareness and sensation during purposeful body-centered movements" (Freiler, 2008). Participants in her research used descriptive language such as 'being in tune' with the body or 'listening to the body' and being 'more aware' of the body as they attended simultaneously to themselves and their surroundings. Similarly, Stuckey (2009) proposes a notion of embodied knowledge as "learning that comes from the body through engagement with the senses and an increased bodily awareness" (Stuckey, 2009). The term 'bodily knowledge' later reflected in the human-food interaction model thus encompasses these nuanced meanings.

Despite the varied approaches to studying embodied knowledge, one consensus across these studies is that knowledge resides in the body before reaching conscious awareness (Damasio, 2010). When it comes to playing the *taiko* for example, taiko is seen as not just an instrument but "the connection between the drum and the player." Thereby, focusing excessively on the technicalities of sound is said to lead to loss of the 'feeling' or 'spirit' behind the playing, reducing it to simply using the drum (Powell, 2004). In another instance, tension is first experienced in the body as a stiff neck, queasy stomach, or a tight jaw, and if we examine the sources of this dis-ease, we may be able to trace it to a particular experience or event (Lawrence, 2012). Drawing on *Taiheki* theory originating from Japanese tradition, spontaneous bodily sensations are said to occur independently of what humans consciously think; and the body's response is synchronous with the human psyche. An illustration of embodied response is the involuntary reddening of the body with an appropriate amount of applied heat. With natural relationships existing between the human subject and his environment, it is said that humans are believed to possess the innate ability to adjust and 'reorder' the body (Noguchi, 1986). This message of unconscious bodily knowledge is in line with what researchers suggests about the body's capacity to guide itself by itself if given the chance.

Based on findings on embodied knowledge, human interaction with our external environments, be it with food or other objects, is both anatomical and instinctual, extending beyond functionality. While embodied knowledge may operate unconsciously, its role in guiding behaviour towards the maintenance and restoration of subjective states of harmony between mind, body and environment cannot be dismissed. In line with this perspective, if the contemporary human-food relationship becomes purely functional and nutrition-focused, humans in modern society run the risk of losing an innate capacity to critically understand experiences and our own nature (Shapiro and Shapiro, 2002). Therefore, rather than seeing the human as a subject of technical proficiency or cognitive ability, an integral model of human-food interaction must represent the role of bodily knowledge and our embodied responses to any given context.

3 Proposal of a human-food interaction system model

Considering the transdisciplinarity of human factors, an analysis of human-food interaction focusing on specific factors or confined to static environments would fall short in capturing the mechanism and consequences of human behaviours in real-world settings. This paper contends that part of the human's natural regulatory mechanism is an intricate human-food interaction system that operates within us individuals, albeit invisibly. To analyse this system, we employ multiple consistent views of the system to represent the system boundary, its contextual influences, internal structures, activities and dependencies. In this paper, we propose a system context diagram, use case diagram and activity diagram to represent the system of human-food interaction.

We initiate a system context analysis to define the system boundary and identify its external associations. A use case diagram is derived from these contextual associations to provide a more detailed breakdown of the scenarios performed by the system. To relate the use case scenarios with the system's functional structures and activities, a system activity diagram is then used to represent the behavioural view internal to the system. These three diagrams provide a comprehensive overview of the model of human-food interaction to serve as a foundation for discussion and iteration based on emergent findings of human knowledge. The result of our proposed system model describes the dependencies across internal human system functions, downstream effects of cognitive biases towards extrinsic motivators of behaviour, potential underlying trade-offs of existing solutions for 'behaviour change' and provides more complete and precise human requirements for designing social systems that consider its impact on the longer-term human lifecycle.

3.1 Context analysis

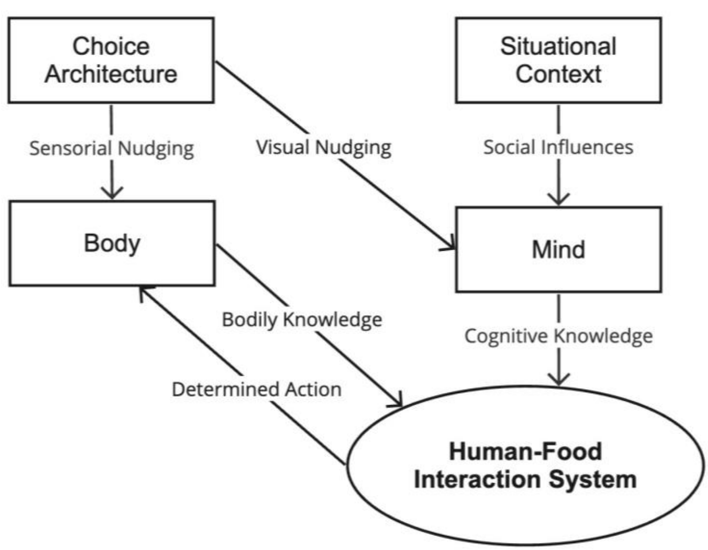
Figure 1 illustrates the context analysis in a system context diagram. *Choice Architecture* signifies the physical infrastructures in our environment, while *Situational Context* represents sociocultural infrastructures that change dynamically according to situations, such as an individual's social environment. These are sources of input into the human system in the form of 'Sensorial Nudging' to the *Body,* and 'Visual Nudging' and 'Social

Influences' into the *Mind*. In this human system definition, Mind and Body represent those of an individual, implying that environmental factors from physical and sociocultural infrastructures influence an individual's mind and body subjectively. The input processed through the mind and body is then used by the human-food interaction system to determine a course of action deemed appropriate by the individual. The body produces Bodily Knowledge while the mind produces Cognitive Knowledge, according to the relevance of psychological messages perceived by the individual. All of these system inputs described in Figure 1 are defined in Table 1 with reference to the relevant literature segments from which they have been derived.

Table 1 System context diagram: terminology and definitions table

System inputs	*Definition*	*Reference*
Bodily Knowledge	Instinctual, spontaneous sensations or reactions of the body in response to environmental and situational circumstances, that occur without the need for conscious awareness or cerebral processing	Sections 2.3 and 2.4
Cognitive Knowledge	Decision outcomes based on mental, emotional, social frameworks of the mind, which could be processed attentively or inattentively by use of cognitive effort or heuristics respectively	Section 2.1
Sensorial Nudging	Refers to a comprehensive, multi-sensory experience that goes beyond individual sensory stimuli	Section 2.2
Visual Nudging	Refers to visual information and external stimuli that is intended to influence decision-making	Section 2.2
Social Influences	Refers to verbal and nonverbal aspects of human communication that is interpreted by the mind to produce associated meaning	Section 2.2

Figure 1 System context diagram: showing the system in relation to an individual's mind and body, and by extension, environmental factors including physical choice architecture and their sociocultural situational context

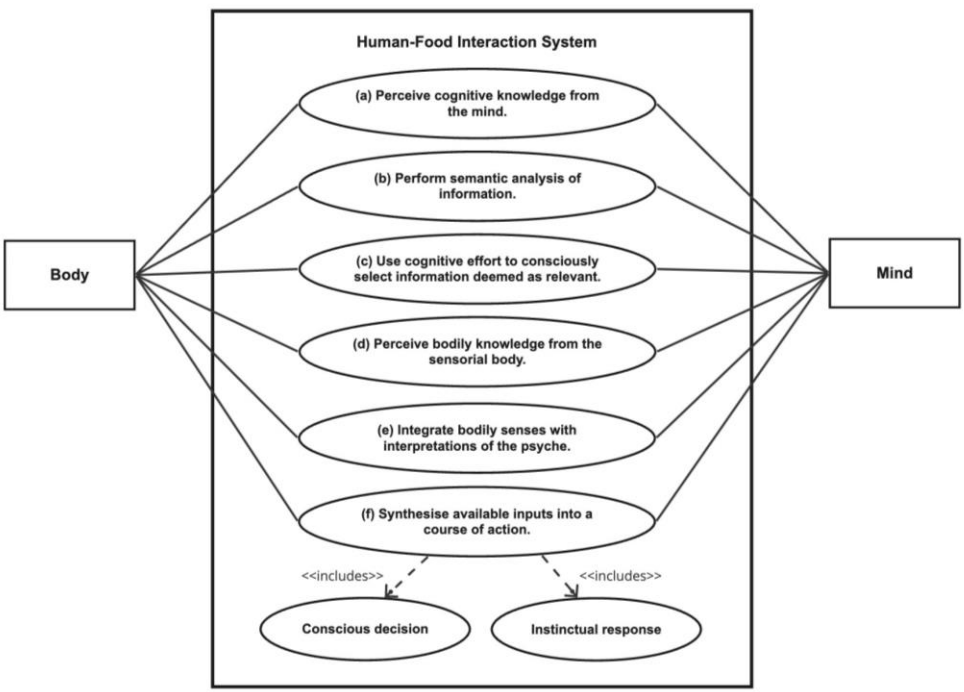


The context diagram describes that psychological and physiological characteristics of an individual would influence their human-food interaction system, which would in turn affect their determined action (i.e., food choice). To simplify its representation, our model is contained to an instance of food decision-making and does not - at its level of abstraction - describe the recursive impact that human-food interactions could have on an individual's mind and body. The model focuses on representing functions and processes that are internal to the system, which include how and what the mind and body communicates (e.g., the gut-brain axis). By describing its internal functions, the system model shows how the human-food interaction system serves as a mediator between the food environment and an individual's behavioural outcome.

3.2 Use case diagram

Building upon the context analysis, the human-food interaction system must integrate inputs from both the mind and body to determine the most suitable course of action for the individual. To do so, we propose that the system will perform the scenarios shown in Figure 2.

Figure 2 System use case diagram: describes the scenarios performed by the human-food interaction system, all of which involve the connection between an individual's mind and body



The system's ability to perceive situational input based on both physical and sociocultural aspects of the context is outlined in use case (a). The capacity of the human to derive meaning from sensory, social, and contextual cues whether consciously or unconsciously is described in use case (b) through the semantic analysis of information. Selective attention occurring while an individual is consciously aware is described in use case (c), where cognitive effort is utilised to select information deemed as relevant. The system also considers the perception of bodily sensations, such as the acceptance or rejection of food, which may manifest as various symptoms; this human experience is considered in use case (d). In line with current literature on embodied knowledge, the body's spontaneous response interacting with the human psyche is represented in use case (e). To determine the appropriate course of action, the system synthesises all available inputs, including that which is conscious and instinctual to the individual, as described in use case (f).

In summary, the use case diagram shows that the human-food interaction system performs and adapts its various functions to the situational context, which would affect internal human processes. It is evident from the diagram that the mind and body are integral to all scenarios, contributing to the performance of the human system as a whole. In reality, the mind and body cannot be seen as separate entities, and the mind-body connection has to be considered in the design of human-social system interactions. However, what remains unseen are the trade-offs between these system functions depending on the influence of the context on the mind and/or body of an individual. For example, if an individual is more rational than instinctual, how would their internal processes and longer-term behaviour differ from an individual who is more instinctual or less concerned with external nudges when making food choices? Conversely, what might be the anatomical effects of external nudging of food behaviours on individuals with different inherent needs? In modern society where nudging is utilised to socially engineer behaviour (see Section 3.2), how are human functions adapting to accommodate these extrinsic cues, and how would this phenomenon affect human sensibilities across the human system life cycle?

4 Human-food interaction model activity diagram

In response to the emergent questions from the use case diagram, this paper uses a system activity diagram to visualise the internal functions of the human-food interaction system. This diagram aims to elucidate the interdependencies and potential trade-offs within the system, particularly concerning the salience of extrinsic and intrinsic motivators for behaviour. In the system activity diagram shown in Figure 3, the system's functions are represented in rounded rectangles, with object flows described using arrows connecting port to port. The functions align with the system's use cases outlined Figure 2, and the way that the functions are connected captures the underlying mechanisms for most scenarios of human-food interactions that could occur.

It can be understood from the diagram that there are essentially two pathways which cognitive knowledge and bodily knowledge are processed when an individual makes food decisions. These two paths are not separate; they converge at function (f) which represents the inseparability of mind and body capabilities. The activity diagram also illustrates how the output of the system ("Determined action") is driven by inputs into each of the functions (a) to (f). Activity (a) to (c) for example, is instigated by selective input from function (a) into function (c). This pathway describes the selective attention that an individual pays to cognitive knowledge from the mind. In the same way, the relationships across others function can be read using their functional inputs. These inputs are defined in Table 2. Depending on the individual's attention to cognitive and/or bodily knowledge, the activity diagram can be used to describe a host of human-food interaction patterns and emergent behaviours. The subjectivity of an individual's relationship and interactions with food is represented in this model.

Figure 3 System activity diagram: illustrating internal functions, interdependencies, and potential trade-offs within the human-food interaction system (see online version for colours)

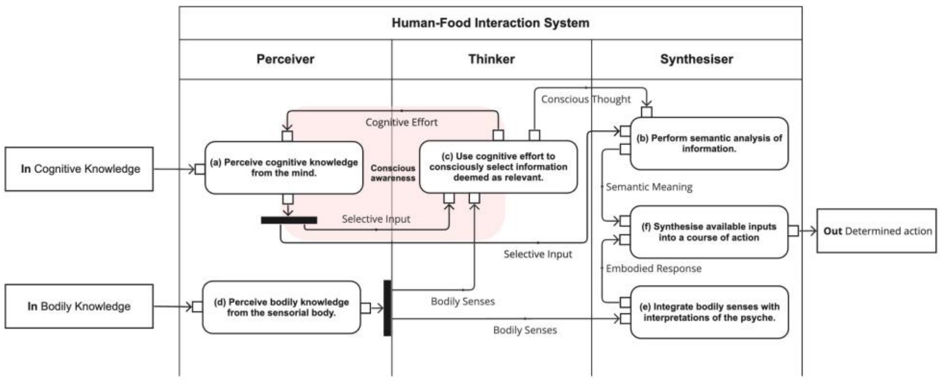


Table 2 System activity diagram: describing functional inputs and their definitions

Functional inputs	*Definition*
Cognitive Effort	Refers to the deliberate mental exertion to rationalise a conscious response to specific tasks
Selective Input	Refers to the information that is parsed through selective attention as attenuated by the individual
Conscious Thought	Refers to the outcome of rationalisation that is contingent on selectively interpreted relevance
Semantic Meaning	Refers to the understanding, interpretation and significance assigned to contextual information
Bodily Senses	Refers to internal sensations, such as a 'gut sense' or other forms of intuition, where interpretations depend on individuals' sensitivity to the internal states of the body
Embodied Response	Refers to bodily-informed outcomes of physical expression and sensations, emerging in reaction to a given situation

Taking a closer look at the model from Figure 3, the system is seen to comprise of three main mechanisms: the *perceiver*, *thinker*, and *synthesiser*, which enact functions (a) to (f). The internal activities of an individual interacting with the external system (food) are delineated as follows:

1 perceiving input from the mind and body

2 expending cognitive effort to contemplate the information perceived

3 synthesising the inputs into a determined action that the individual will perform.

It is evident from the activity diagram that conscious awareness through cognitive effort is merely one way of knowing; and in reality, human intelligence transcends cognition, encompassing knowledge that originates from the body itself. The diagram also suggests that embodied knowledge seems to bypass daily awareness, especially when attenuated by more salient situational input from an information-prevalent society. We further elaborate on the activity diagram using a specific example of human-food interaction in Figure 4.

Figure 4 Instance of the system activity diagram: superimposed with an example of human interaction with a marketed food product. System activities show the behavioural outcome of cognitive bias (see online version for colours)

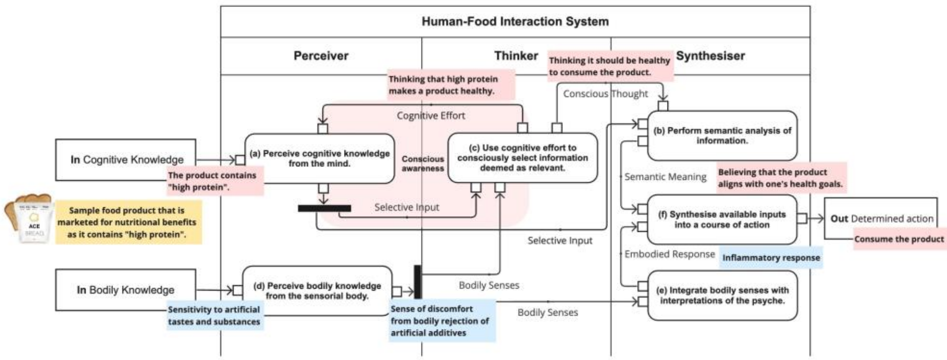


Figure 4 describes the scenario where an individual encounters an informational nudge, such as the packaging of a food product marketed for its supposed nutritional benefits – in this case, "high protein" content. Visual information on the packaging is perceived through the individual's mind and body, with the degree of relevance of cognitive knowledge and bodily knowledge being contingent on the individual's mental model. In this case, the individual is said to be more sensitised to cognitive stimuli compared to their bodily senses, such that cognitive knowledge would appear more salient than bodily knowledge. Assuming that the individual equates higher protein content to greater "healthfulness" of a food product, he is likely to think that it would be healthy to consume the product. If this thought aligns with the individual's identity, i.e., the product marketing aligns with their health goals, then he is more likely to consume the product. With reference to the activity diagram, internal to this individual is a mental process that could supersede more subtle bodily knowledge. As denoted in Figure 4, the individual could have experienced discomfort or rejection towards artificial additives in the product but neglect to recognise or pay attention to these embodied responses. His bodily senses could have been attenuated by beliefs or rationalisation. Using this scenario, the model is seen to demonstrate how the salience of cognitive stimuli and socially-acquired (nutritional) beliefs could reinforce interaction patterns that eventually desensitise individuals to their bodily knowledge and adversely impact their overall health and well-being.

4.1 *Insights gleaned from the model*

Below are propositions of the insights that can be gleaned from the system model thus far:

1 Sensitivity towards subjective bodily knowledge can moderate sustainable food behaviours. Since human intelligence extends beyond cognition and conscious

awareness, it would be imperative to elevate human consciousness and encourage individuals to become more aware of their unconscious needs and tendencies (function (a)). We infer that a step forward to enabling individuals to make appropriate, self-sustainable food choices is to sensitise individuals to their often-unconscious embodied knowledge.

2 Cultivating awareness of heuristic biases can counterbalance cognitively-dominant extrinsic behaviours with more bodily-informed human-food interaction behaviours. Semantic analysis of external information can occur both while individuals are attentive or inattentive (function (b)), and it can be said that individuals have the agency to choose to rationalise their response to given stimuli or default to familiar outcomes. However, erroneous or suboptimal choices often result from decisions influenced by salient distractors in the mind before selective attention isolates relevant sensory information (Teichert et al., 2014; Hunnes, 2016). Therefore, if consumers became more aware of environmental distractors such as certain types of economical nudging, and also continually refine their mental models to discern relevant information, then it seems possible that more people would develop the propensity to choose foods based on intrinsic, bodily drivers.

3 Harmony of an individual's mind and body activities is essential for long-term well-being. The model illustrates that the mind and body are structurally and functionally connected (function (f)). Consequently, behaviour is dependent on the weightage of relevance which individuals place on mind and body functions. If the environment were to reinforce selection biases towards cognitive knowledge by augmenting the importance of visual information or social influences, we can infer that an individual's sensitivity to their bodily knowledge could be impeded over repeated exposure. Since individual resources for perceiving input into the system are shared across perceiving cognitive knowledge and bodily knowledge, then bias towards cognitive ways of knowing would entail increasing numbness towards embodied ways of knowing. As supported by existing literature (Section 3.2), disharmony of the mind and body is correlated with diseases over the human lifecycle.

4 Integrating mind-body knowledge to regulate behaviour is part of the human system's innate capabilities. Enabling more precise perception and synthesis of available inputs into the human-food interaction system could therefore be the point of leverage to transform how we engage with and experience food. Based on the model, we suggest that further studies into the process of human synthesis is warranted, as current discussions are primarily focus on its application in the design field (Kolko, 2007).

5 Evaluation

In this research, five domain experts based in Singapore were interviewed to review our system model. The experts are practitioners across the fields of clinical dietetics, clinical psychology, public health education, and/or are currently involved in food and nutrition-related public health initiatives at the times which they were interviewed. They have been deliberately invited from different backgrounds and practicing contexts to provide for varied yet related perspectives that could validate the accuracy of our transdisciplinary system model.

The interviews were conducted 1 : 1, remotely via video conferencing, to leverage the function of sharing screens to easily follow their observations and focal points on the diagrams in real time as the conversations unfold. The experts were asked semi-structured, open-ended question on their understanding of the mechanisms underlying human-food interaction, followed by questions on how accurately or inaccurately the model reflected their knowledge and experiences. To validate the model, the experts brought in anecdotal evidence of problematic food behaviours which we traced using the system activity diagram. The case study presented in Figure 4 is based on one of many examples that were raised by our experts that could be explained using the system model. In our interviews, the experts were not probed for specific evidence nor asked to superimpose their experiences onto the system model. This research finds that all of their perspectives and case studies aligned with the mechanisms represented by the model, adding to the richness of inferences from the system model. The process of validation with our domain experts is reflected in a documentation of successive iterations of the system activity diagram (Supplementary Table S1); these iterations precede the final model presented in this paper.

5.1 Key observations by domain experts

The following object flows in the activity diagram illustrate key observations by our experts, of systemic issues pertaining to human-food relationships in modern society:

1. **(a) → (b):** Describes the interpretation of information that bypasses daily awareness. Experts say that this entails the risk of developing food habits based on mistaken beliefs rather than bodily requirements. One of our experts – a senior clinical dietician – highlighted that individuals, especially parents and the elderly, would often rely on social influence to make certain food decisions: "they go by hearsay rather than really understanding deeper with regards to where they get the information." The fast spread of socially acquired information, amplified by social media, poses a challenge for experts to reshape such unconscious beliefs.
2. **(a) → (c) → (a):** Represents a reinforcing loop indicating how an individual can identify with certain types of information more than others; it can happen when an individual attaches mental labels to food knowingly or unknowingly. Our experts pointed to specific at-risk groups, typically referred to as 'healthy eaters' or 'over-exercisers,' who would follow strict diets and tend to label foods in binary 'good' or 'bad' terms. Such groups of people are at risk of losing their sensitivity to their bodily knowledge, compromised to fad diets and fallacious beliefs. Clinical experts mention of a worrying increase in the number of patients in recent years, who have been referred to dieticians to receive dietary advice because these individuals have "become rigid and not intuitive". In such cases, excessive reliance on information has led to detrimental effects on their natural interaction with food.

5.2 Insights from expert suggestions

Our experts emphasised the importance of recognising and questioning social standards that modern society is exposed to in the food environment. The reinforcement of self-identity and mental labels towards food can augment the salience of external information. Mental associations could become a default leading to behavioural processes that bypass the awareness of an individual. With the prevalence of misinformation in modern society, it is critical to heed one's innate voice to support reasoning rather than to passively believe the everchanging landscape of social influences. Having the agency and awareness to select relevant information that is one way to moderate the effects of external influence and downstream impacts on individual health and well-being.

From a social systems design standpoint, the modern-day phenomenon of blind trust (Xiao et al., 2021) prompts us to question the standards that people, and their behaviours are measured by. Some of our experts have pointed out that the food system in modern society can be too rigid, such that "it is almost unthinkable to ask to alter an order in a restaurant that offers standard menu items". Customer requests are often rejected even when the food establishment has the resources to accede to such requests. By this example, the experts do not imply that more flexibility or customisation should be introduced in food establishments, but rather, the rigidity of social systems exemplified by reluctance in accommodating minor adjustments in food orders reflects a broader issue of the over-emphasis on economic efficiency and standardisation. While it seems that systemic intervention is required, caution is advised not to intervene in haste. Hasty interventions are associated with risks of short-sighted measures with longer-term repercussions. Citing Barker's Hypothesis (1990), one of our experts emphasised the need for more precision in defining human requirements for behavioural interventions to avoid unintended long-term consequences on the human's self-regulating mechanisms.

5.3 Limitations and future work

In summary, the model supports the importance of harmonising bodily knowledge and cognitive knowledge, which becomes more apparent when we observe the underlying mechanisms for how individuals interact with their environments. The model does not argue that either form of knowledge is more correct, for there will be situations where rationality appropriately trumps intuition and vice versa. Instead, this paper implores consideration of the human system lifecycle when it comes to behavioural nudging. We place emphasis on the discussion that an over-reliance on external information and cognitive rationalisation to make decisions is likely to compromise bodily sensitivities over time. As such, social system designers advocating for human resilience ought to consider how the external system's architecture would affect deeply rooted interaction patterns, and thereby affect an individual's innate self-regulatory mechanisms. Nonetheless, we acknowledge the obstacles in designing social systems for long-term impact due to the limitations in verification methods.

While the current system model is grounded in verified human factors and theories, verifying the model itself via conventional metrics remains a practical challenge due to the elusive nature of the internal human functions and activities it describes. To conduct empirical tests of human-food interactions and their longer-term effects on the entire human system is inherently complex. In light of these limitations, we outline two potential directions for future research based on this model as follows:

1. Investigating mind-body interaction with regards to visual nudging. We hypothesise that amplifying informational input to the mind would distract an individual from sensing their bodily responses towards food. Assuming that bodily knowledge can be detected using various bio-signals and assessed by observing their changes, then it could be feasible to analyse the impact of various forms of behavioural nudging on the human system as a whole. We foresee that being able to distinguish different internal effects of nudging could help social system designers make better informed decisions about their system requirements.
2. Reconsidering the role of nudging. Given that biases toward extrinsic behaviours could compromise human intelligence in the long run, the system model supports a paradigm shift in the design of social systems to foster innate human intelligence in an artificially-intelligent modern world. Behavioural nudging, which is often used to influence behaviour from the outside-in, can be reframed to promote greater awareness of bodily knowledge and shift its proposition from capitalising on human unawareness to encouraging bodily-informed behaviour. This direction is intended to improve the balance between mind and body engagement through human-environment interactions.

6 Conclusion

In conclusion, the integral model of human-food interaction captures a comprehensive spectrum of human factors to elucidate how human behaviour on the whole is more than the sum of its parts. The model-based systems approach used provides the visualisation and tangibility necessary to bridge abstract concepts of human knowledge with real manifestations of food behaviours. At the same time, this research demonstrates the importance of keeping the whole in mind even as we delve deeper into specific mechanisms of the human system; for the more successful we become at studying parts of the human in isolation, the less likely our data and simulations would reflect the subjective needs and dynamic behaviours of humans in the real world.

As far as our current system model goes to show, designing choice architecture and other social infrastructures for sustainable human-food interactions should be built upon the awareness of how humans synthesise interoceptive and exteroceptive information, and how individuals are innately capable of guiding their own behaviour towards homeostasis within themselves and with their environments. Without such acknowledgement of the intricacies of human functions, behavioural interventions run the risk of perpetuating unsustainable mental models and food-related behaviour, while compromising individuals' sensitivity to their embodied knowledge. While this model is by no means finished, it effectively serves as a springboard for discussion and collaboration surrounding advanced research on the role of bodily knowledge. We are hopeful that more combined efforts to foster sensitivity towards the human system's embodied responses in various human-environment interaction contexts would benefit the well-being of individuals and future society.

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Competing interests

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Data availability

Data sharing is not applicable to this paper as no datasets were generated or analysed during the current study.

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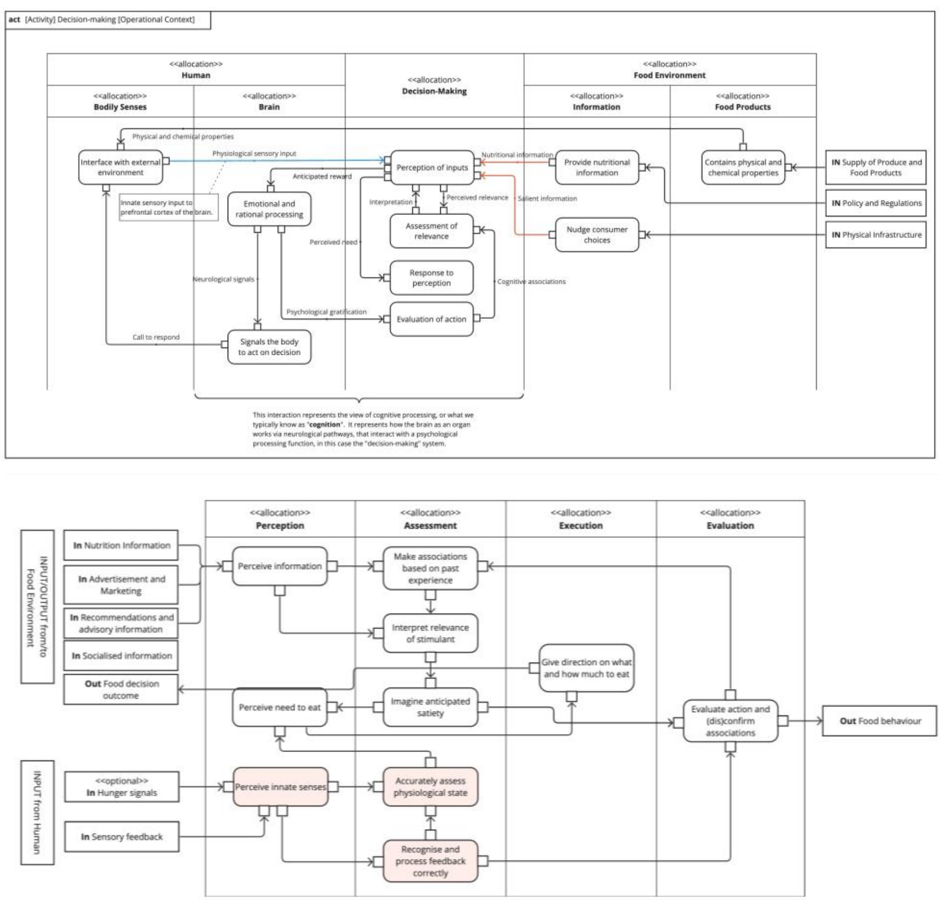
Supplementary Material

Table S1 A compilation of previous iterations of the system activity diagram. These represent pivotal points in the model validation and development process (see online version for colours)

System activity diagram iteration log

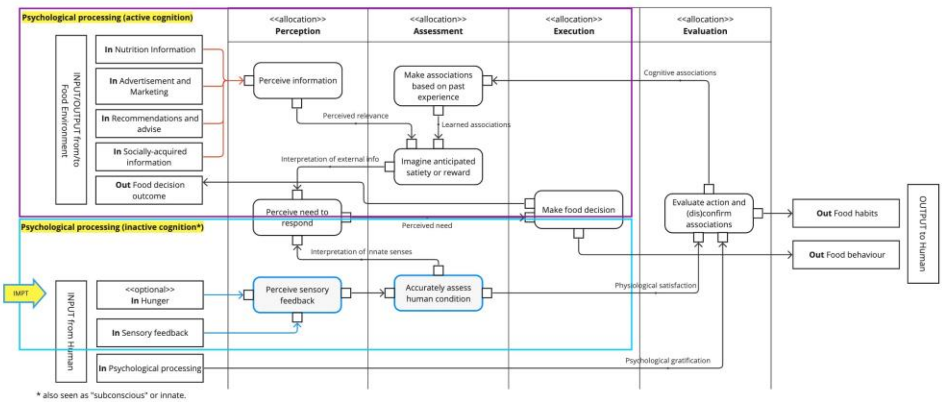
Key Iteration 1

Activity diagrams of operational context (top) and proposed system (bottom)



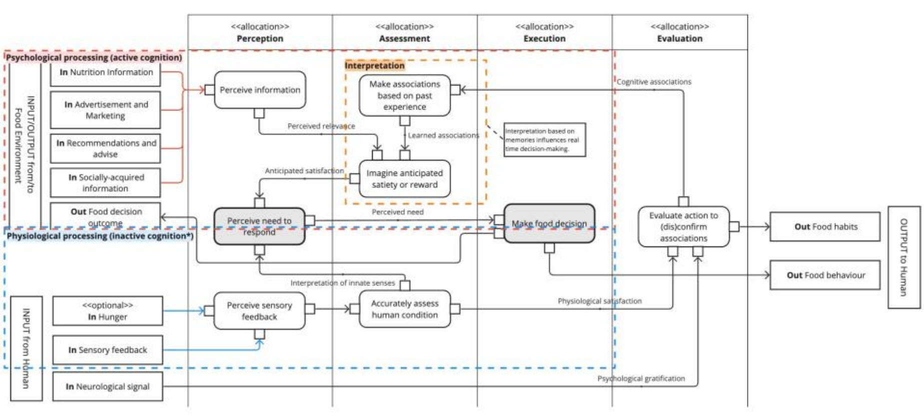
In this preliminary iteration, the activities of the human-food interaction system (previously: food decision-making system) were discussed in relation to its operational context to derive its internal functions and mechanisms. Functions within the system model were allocated to four overarching mechanisms: Perception, Assessment, Execution and Evaluation. The inputs from the Food Environment into the system were derived from previous drafts of the context analysis diagrams and use case diagrams, which borrowed terms from various prior studies. This led to the inclusion of input types such as “Nutrition Information”, “Advertisement and Marketing” and so on. In a similar way, this diagram tries to distinguish the types of inputs from the human body into the system. In a way, this diagram is a visual representation of the disparity of information which the authors managed to find in literature regarding human cognition and psychology, as compared to the instinctive body. The relationships between each of the functions in the system activity diagram above had been mapped based on interpretations of theories from existing literature and how these theories connect across disciplines.

Key Iteration 2



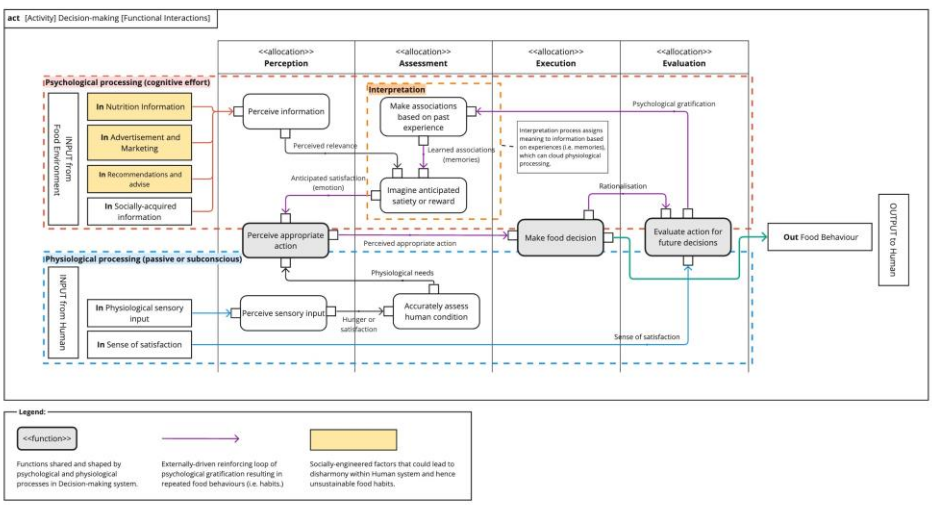
From Iteration 2 of the system activity diagram, we began to see and attempt to describe two pathways in which inputs from the mind and body seem to be processed. The distinction is that one pathway was seen to require active cognition for certain functions to occur, whereas the other does not. Based on these assumptions, the model at this juncture started to represent variable perspectives on human behaviour, highlighting the difference between cognitive theories and other more sensorial views beyond psychology

Key Iteration 3



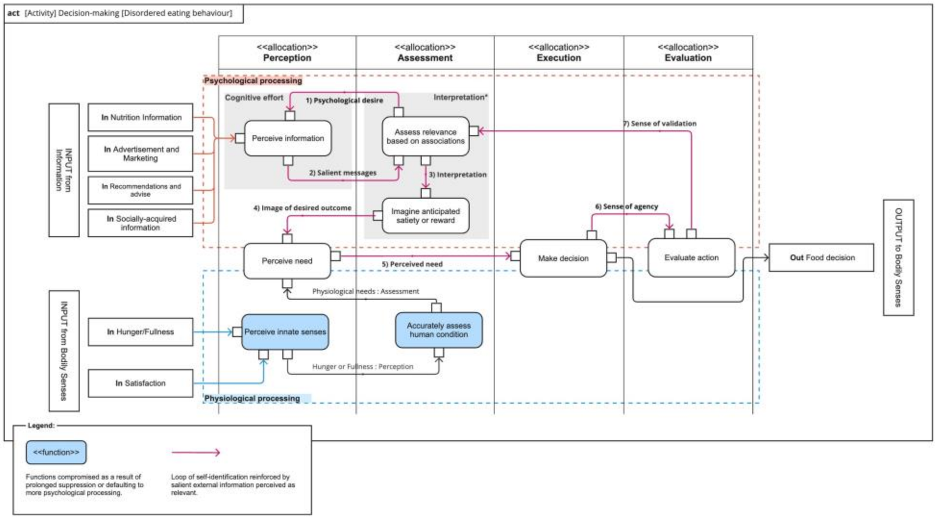
In Iteration 3, it was established that the lower half of the system activity diagram more accurately represents input from the sensorial body, such as ‘Hunger”, “Sensory feedback’ and “Neurological signal”. These terms were mainly referenced from studies related to human physiology. The two pathways were hence renamed accordingly. The functions in grey represent the convergence of psychological and physiological processing, as a visual indicator of how the mind and body are inherently connected and cannot be analysed as separate entities. Our interviews with experts using this diagram had also led to the discussion on certain functions in the model that represent subjective interpretation. Iteration 3 was validated in the sense that these mechanisms represent how interpretation affects decision-making outcomes (i.e., food choices); and also, the model represents how external information that we take in from the environment is socially engineering behavioural outcomes. The model manages to represent behaviour as a systemic outcome of infrastructural conditions – both physical and cultural. Not only is the model seen as valid, but it provides value as a tangible artefact to communicate the real, subjective needs of individuals in modern society. Experts compared discussing the internal human system model it to discussing “mindfulness” – a traditional concept that somehow people only began to communicate more actively in more recent years.

Key Iteration 4



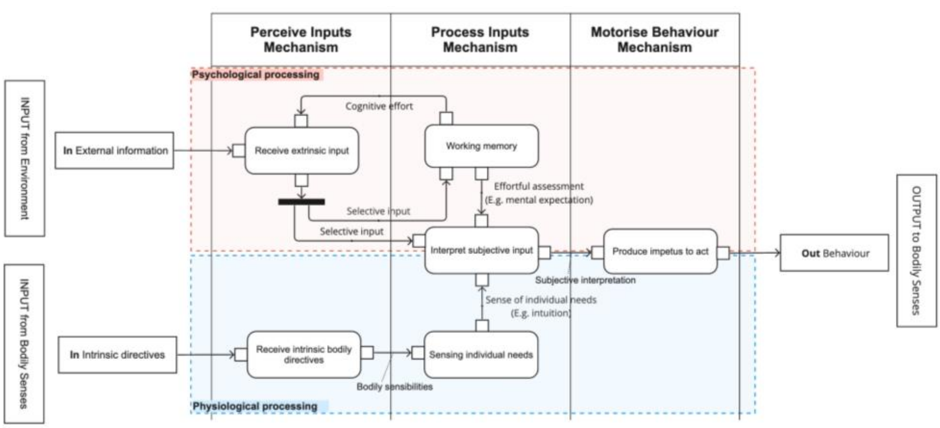
Iteration 4 represents an attempt to highlight the interpretations and insights surfaced by our domain experts from studying the model. The functions shared between psychology and physiology are highlighted in grey, the inputs that seem to be socially-engineered to influence behaviour are coloured in yellow, and a critical reinforcement cycle is outlined with purple arrows. Instead of separating outcomes of ‘Food behaviour’ and “Food habits”, which are often used interchangeably and can hence cause confusion, the reinforcement loop in the model was used to explain how psychological beliefs that are reinforced would affect the longer-term food habits of an individual. In this way, the system model represents both immediate situational outcomes (food choices) and also, how repeated interaction patterns could result in certain types of food behaviours in the long term. If an individual’s perception is biased towards psychological inputs, it can be inferred that their behaviours are more likely to change with the environment. Considering the dynamic and volatile modern-day society, such individuals are more likely to display behavioural inconsistencies or unsustainable food and health-related behaviours.

Key Iteration 5



Iteration 5 tries to describe the subjective influence of extrinsic factors on individual food behaviour and highlight the potential consequences of cognitive biases on the human system. The functions coloured in blue represent the individual's sensitivity to their intrinsic needs which could be compromised as a result of attenuating bodily senses in favour of external stimuli. The magenta coloured arrows in the upper half of the activity diagram illustrate how an individual may identify with certain extrinsic drivers of behaviour (e.g., socially-acquired information). In this diagram, self-identity is represented as a psychological desire (1) that is projected unto external information, which is then perceived to be salient due to its relevance to the individual's sense of self – which may or may not be helpful to the individual, depending on whether it is harmonious with the individual's real needs. According to our experts, the system model can be used to explain the case of disordered eating habits found in an increasing number of clinical patients. The fact that both a harmonious and discordant relationship between the mind and body can be represented via the system model is a testament to its validity.

Key Iteration 6



Iteration 6 illustrates the system model at higher-level of abstraction to more accurately represent the broad range of human-food interaction scenarios that can occur in reality. An even deeper evaluation of the model proved that some functions could be collapsed and/or simplified, and it was found that sharper questions could be evoked from a cleaner model. For example, the situation of nudging and its subjective impact in the short- and long-term could be discussed with this model. The mechanism of nudging is not explicitly carved into the model, which is precisely the point; semantic meaning in certain types of nudges could be filtered by conscious thought or by autonomous selection, which leads to variable effects on individuals.

It was also decided that the functional mechanisms would be renamed to prevent confusion. 'Execution' and 'Evaluation' from previous diagrams have been merged into a 'Motorise Behaviour' mechanism to prevent the misunderstanding that this system would perform the decided action. This system instigates S individual to act, and by itself represents an invisible network of activities that occurs inside the human system. Eventually, these mechanisms were again renamed as simplified nouns in the final iteration. The main reason is to avoid associations of this model with concepts from any particular discipline that may have context-specific definitions for action-oriented words such as 'perception', 'processing', and 'motorise'. The human-food interaction system represents a novel system model derived from transdisciplinary research, whose architecture is not dominated by a particular domain. This point is clarified by revising the naming conventions in the final system model. Several other decisions were made based on insights from collective discussions, leading up to what we think is currently the most useful model of the system presented in the manuscript.