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Grand challenges in human-food interaction☆

Florian 'Floyd' Mueller [a,*], Marianna Obrist [b], Ferran Altarriba Bertran [c], Neharika Makam [d], Soh Kim [e], Christopher Dawes [f], Patrizia Marti [g], Maurizio Mancini [h], Eleonora Ceccaldi [i], Nandini Pasumarthy [j], Sahej Claire [e], Kyung seo Jung [k], Jialin Deng [a], Jürgen Steimle [l], Nadejda Krasteva [m], Matti Schwalk [m], Harald Reiterer [n], Hongyue Wang [a], Yan Wang [a]

[a] Department of Human-Centred Computing, Exertion Games Lab, Monash University, Melbourne, Australia
[b] University College London, London, UK
[c] Escola Universitària ERAM, Universitat de Girona, & Gamification Group, Tampere University, Salt, Catalonia, Spain
[d] Carnegie Mellon University, Pittsburgh, PA, USA
[e] Stanford University, Stanford, CA, USA
[f] Department of Computer Science, University College London, London, UK
[g] University of Siena, Siena, Italy
[h] Department of Computer Science, Sapienza University of Rome, Rome, Italy
[i] CasaPaganini - InfoMus, DIBRIS, University of Genoa, Genoa, Italy
[j] HAFP Research Lab, RMIT University, Melbourne, Australia
[k] Stanford Center at the Incheon Global Campus, Incheon, South Korea
[l] HCI Lab, Saarland University, Saarland Informatics Campus, Saarbrücken, Germany
[m] Sony Europe B.V., Stuttgart, Germany
[n] HCI Group, University of Konstanz, Konstanz, Germany

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ABSTRACT

There is an increasing interest in combining interactive technology with food, leading to a new research area called human-food interaction. While food experiences are increasingly benefiting from interactive technology, for example in the form of food tracking apps, 3D-printed food and projections on dining tables, a more systematic advancement of the field is hindered because, so far, there is no comprehensive articulation of the grand challenges the field is facing. To further and consolidate conversations around this topic, we invited 21 HFI experts to a 5-day seminar. The goal was to review our own and prior work to identify the grand challenges in human-food interaction. The result is an articulation of 10 grand challenges in human-food interaction across 4 categories (technology, users, design and ethics). By presenting these grand challenges, we aim to help researchers move the human-food interaction research field forward.

1. Introduction

There is an increasing trend in combining interactive technology with food, embraced under the term "Human-Food Interaction" (HFI) (Khot and Mueller, 2019). For example, there are apps that allow tracking food intake to achieve diet goals (Silva et al., 2011), kitchen tools that connect to food databases on the internet (Thermomix, 2022), robots that help with cooking (Zhu and Chang, 2020), natural language and image processing systems that personalize recipes (Li and McAuley, 2020), big data systems to create culinary menus (Varshney et al., 2019), and projected visuals on the dining table to support the eating experience (Hagger, 2018). Food is not only essential for our survival but also provides some of the most fundamental pleasures of life (Brillat-Savarin, 2009). Hence, combining it with interactive technology offers unique opportunities, but also poses unique challenges when compared to traditional interaction design, such as that the material of interaction is perishable. In particular, it is believed that HFI offers opportunities to enhance the way we engage with food, possibly leading to a healthier diet (Marshall et al., 2022) and enriching the social benefits gained from eating together (Barden et al., 2012), leading to improved health and

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* Corresponding author.
E-mail address: floyd@exertiongameslab.org (F.'. Mueller).

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wellbeing. However, HFI work could also lead to negative outcomes. For example, reducing the complexity of eating, turning the richness of food practices into bland experiences only concerned with optimal energy intake (Choi et al., 2012; Grimes and Harper, 2008). One prominent negative example is the use of mobile phones at the dinner table, resulting in mindless eating and hindering the social benefits of eating together (Ferdous, 2015).

We consider HFI within Human-Computer Interaction (HCI) as being concerned with using interactive technology to enhance, enrich or transform the food experience. Although technology can play a role in the larger food context, such as by providing resource management systems for agriculture, sourcing advice systems for wholesalers, and online recipe database search functions, in this article we focus on the food experience that is concerned with eating the food (Altarriba Bertran, Jhaveri, Lutz, Isbister, and Wilde, 2019). So, our interactive technology discussions are specific to the fact that the food is being eaten by humans. As such, our scope is restricted to the food experience by humans and does not consider topics like, for example, the production of food for animals or the growth of eatable produce that is not meant for human consumption. We scoped this article in this way because we believe that the food experience offers opportunities, but also challenges, that we want to examine first before we delve into more tangential areas. The challenges stemming from a rather unique combination of characteristics touched upon in prior non-food HCI work, however, come together strongly in an intertwined way that is specific to HFI. For example, HFI is concerned with food, a tangible and perishable material. Hence, HFI can draw upon tangible interactions (Shaer and Hornecker, 2010) and ephemeral interface research (Doering et al., 2013). However, this prior research has not yet fully investigated what happens if the user eats the interaction's material, that is, the food (Wiberg, 2018; Deng et al., 2021, 2022, 2023a–c; Deng and Mueller, 2023; Mueller et al., 2021). Furthermore, HFI involves more than one sense (therefore, it is not just concerned with taste, but also how a dish looks, how it smells, how its texture is perceived, what sound it makes when biting, etc. Spence 2021). Hence, HFI can also build upon research on multisensory interactions. However, the associated research community has not yet fully understood the specifics of multisensory eating (Carlos Velasco and Marianna Obrist, 2020). Additionally, HFI's interest in eating highlights an interaction that everyone *needs* to do (otherwise, they risk severe health implications). Hence, HFI shares similarities with ubiquitous computing and, in particular, its use of biosensors, as this research is also interested in non-optional interactions such as implicit interactions. However, this research area does not tell us much about these interactions regarding food. Moreover, HFI is concerned with the consumption of food, mostly multiple times a day, which is deeply cultural and socially embedded (Locher et al., 2005). HCI research involving ethnographic approaches and alike has previously aimed to understand such practices, hence, HFI can build on this prior work. However, how to turn this understanding into system design is still underdeveloped.

We would argue that the above list suggests that the HFI field is complex and multi-disciplinary, and possibly even fragmented (Altarriba Bertran, Jhaveri, et al., 2019; Bertran et al., 2018; Min et al., 2019). Specifically, not only does HFI involve the augmentation of user experiences, but it also focuses on the biological and chemical foundations of taste, the understanding of food production systems, the application of technology across these systems, and the overarching societal underpinnings of food engagements and the societal influences on behaviors. On the one hand, this makes it very exciting to work in HFI, but on the other hand, it also makes it challenging, as not much guidance exists, such as in the form of a set of grand challenges that offers a coherent structure on how to bring the field forward. Other emerging sub-fields of HCI (such as social robotics (Tapus et al., 2007), crowdwork (Kittur et al., 2013), human-computer integration (Mueller et al., 2020), shape-changing interfaces (Alexander et al., 2018), immersive analytics (Ens et al., 2021), and information retrieval (Belkin, 2008)) have previously faced a similar predicament. To address this, they have articulated "grand challenges", a set of major current or potential limiting factors that can serve to form an agenda to identify and steer the direction of future research (Shneiderman et al., 2016). Just as these prior grand challenge articulations have advanced their respective research fields, we hope that our work will similarly move the HFI field forward.

We believe that, aligned with the prior grand challenge works we mentioned above, identifying the grand challenges is an important step to guide future research. Hence, in this article, we present 10 grand challenges in HFI across four categories, technology, users, design and ethics, inspired by prior work that used similar four categories (Alexander et al., 2018; Mueller et al., 2020). One of these seminars even used the same venue (Mueller et al., 2020). The 10 grand challenges are summarized in Table 1. We invited 21 HFI experts to a 5-day seminar. The goal was to review our own and prior work to identify the grand challenges in HFI.

We believe that our articulation of the grand challenges in HFI can help:

- researchers currently not working in the HFI area identify where they can contribute, bringing them into the field;
- researchers currently working in the HFI area to situate their work within a larger research agenda, leading to a more coherent vision of the field;
- students, such as Master and PhD candidates, to pick research topics within HFI that advance the field forward rather than rehashing existing areas of investigation;
- industry practitioners to see where the field could be heading, helping them to prepare for future HFI applications that emerging technologies enable;
- grant providers to assess the state-of-the-art of the HFI field in order to provide targeted support such as funding.

Taken together, with our articulation of the grand challenges in HFI, we believe we can better help to navigate and coordinate this exciting research area, collaboratively explore the emerging opportunities and also collectively reflect upon the associated responsibilities when designing future food experiences.

2. The evolution of HFI

We now present the evolution of the HFI field to indicate the state of the art that our grand challenges build upon. This section surveys prior efforts from various perspectives to bring the diverse field together into a more coherent whole to create a basis for the emerging area that HFI is. Such efforts include definitions of HFI, surveys of HFI, HFI workshops, symposia, and seminars, as well as journal special issues on HFI.

Several authors have proposed definitions of what HFI is (and what it is not) to sharpen future research's focus. For example, Choi et al. defined HFI as "the interconnection between the self and food" (Choi et al., 2014). Relatedly, Khot et al. defined food practices as "any human activity in which food is involved, ranging from agriculture, food

Table 1
Grand challenges in HFI.

Technology	Users	Design	Ethics
Sensing taste	Supporting creative practitioners	Dealing with the taste experience's complexity	HFI *for* and *as* sustainable practice
Synthesizing food	Evaluation frameworks for HFI	Identifying interactivity opportunities in food scenarios	Applying HFI ethically
Food as interaction material		Designing new forms of commensality	

preparation, eating, gifting food, sharing meals and cleaning up" (Khot and Mueller, 2019). Symons refers to these practices as "the human food cycle" (Symons, 1994). This led Khot et al. to consider four phases of HFI: growing, cooking, eating and disposal (Khot and Mueller, 2019). In our seminar, we considered the above definition of "human activity in which food is involved", but focused on technology-mediated interactions, hence our grand challenges are concerned with those.

Over the past years, the field has produced an increasing number of publications, and as a result, there have been efforts to summarize them in the form of surveys (Altarriba Bertran, Jhaveri, et al., 2019; Bertran et al., 2018; Min et al., 2019). Many papers describing and evaluating systems that are concerned with eating have been captured in these surveys, which has enabled a series of workshops, symposia, and seminars, which we describe next.

For example, there have been workshops accompanying HCI conferences (Altarriba Bertran, Duval, et al., 2019; Choi et al., 2012; Clear et al., 2013; Comber et al., 2012; Davis et al., 2020; Dolejšová et al., 2019, 2018; Kuznetsov et al., 2016; Raturi et al., 2017; Vannucci et al., 2018). There have also been symposia on HFI (Foodchi, 2022) and social interest groups (Khot et al.). Stanford organizes a "Food Innovation & Design" symposia annually along different themes such as sustainability, health, joy, culture, and more (Kim, 2022). A recent workshop at CHI 2021 aimed to investigate the "future of human-food interaction", asking what is next for the field. The need for an articulation of grand challenges was discussed, as there was general agreement that such an articulation, which other sub-fields of HCI had previously benefited from, is still missing in HFI (Deng et al., 2021). Therefore, as having such an articulation might also be beneficial for the HFI field, we organized our seminar.

A prior food seminar resulted in a manifesto to enable an inclusive future for HFI (Obrist et al., 2018). The participants argued that designing interactive systems around food requires careful consideration of what one could do with such technology (use and misuse). Educating people is the most urgent action the seminar called for to prevent mistakes. Educating people means training their critical thinking, which is often ignored when we eat and when it comes to what we eat, and how that impacts others and ourselves, the participants believed. In our seminar, we, therefore, also tried to capture such societal impacts in our grand challenges.

A special issue on "human-food interaction" asked how researchers should engage with the complex disciplinary, political and cultural landscape of the HFI field (Khot and Choi, 2018). More recently, a 2022 Frontiers Research Topic journal special issue (Frontiers, 2022) asked for contributions on commensality-related research in psychology and computer science. We believe that these prior efforts highlighted the deeply socially embedded practice of eating, which we aimed to reflect in our grand challenges, especially around how social aspects of eating (e.g., eating together in the same shared space, or remotely) could be technologically augmented.

Taken together, although these prior efforts helped to create a basis for the emerging area that HFI is, there is still no comprehensive structure articulated that could guide future HFI work, such as in the form of grand challenges. In response, we conducted a seminar where we aimed to articulate grand challenges in HFI.

3. Approach of identifying grand challenges in HFI

Our approach was primarily based on a week-long seminar that was established to review our own and prior work and identify the grand challenges in Human-Food Interaction. Of course, other approaches to a seminar are possible, such as systematic literature reviews (Kittur et al., 2013; Tapus et al., 2007), one-day workshops (Vannucci et al., 2018) or interviews with practitioners using HFI systems. However, as the HFI field is still emerging, we opted for our approach for now and leave complementary approaches (such as utilized for other, more established, HCI sub-fields like "sustainability" (DiSalvo et al., 2010), "the home" (Desjardins et al., 2015), and "reflection" (Baumer et al., 2014)), for future work, acknowledging that they could nicely complement our results.

3.1. Participants

21 people participated in the seminar (M age = 38.8, SD age = 11.9, range = 21 to 61 years). Participants came from a broad range of both academic and private institutions located in the USA (4), Australia (4), Germany (4), Italy (3), the UK (2), Spain, Finland, Japan, among others. The primary research fields of participants varied from design backgrounds (7), computer science (3), medicine, cognitive science, psychology, sociology, engineering, HCI, material science, and multimedia with an average of 3.5 years of experience specifically in HFI (SD = 2.6, range = 0.8 - 10 years). Seven participants were vegetarians, four were flexitarians, and the remainder reported no specific dietary preferences.

Participants were invited because they had designed, taught, deployed or studied HFI systems. A selection of HFI systems we discussed at the seminar is illustrated in Fig. 1. For example, capacitive touch sensors made of edible material that can be embedded in pastry to detect user interaction (Marion Koelle et al., 2022), an interactive plate that plays sound effects when the diner uses their fork to take off a piece of cake (Mueller et al., 2018, 2020), an interactive ice cream cone that uses capacitive sensing to detect licking actions to play music (Wang et al., 2020a), a set of logic gates made out of edible material that allows diners to computationally reconfigure their dessert's flavor (Deng et al., 2022); examinations into the influence of multi-sensory eating experiences in virtual reality (Obrist et al., 2019; Arnold et al., 2018; Mueller et al., 2019), and an artificial dining companion, providing commensal experiences for participants eating alone (Ceccaldi et al., 2020).

3.2. Discussion process

The seminar began with introductory talks by the organizers. This included explanations of why this seminar is topical now (due to an increase of interactive systems emerging around food-related topics), necessary (there are also systems emerging that could be considered "gimmicky" and many research works repeat prior endeavors, suggesting that the HFI area could be at a point of stagnation), and needed (the world faces considerable challenges around food, such as overeating, hunger and food waste). These talks also included insights from prior works on grand challenges in the other HCI sub-fields mentioned above (Alexander et al., 2018; Ens et al., 2021; Mueller et al., 2020), including a realization that most of these prior grand challenges could be roughly grouped into (as papers already suggested (Alexander et al., 2018; Ens et al., 2021; Mueller et al., 2020)): technology, users, society, and design. Hence, we also started with these groupings and complemented them with an "other" category to allow for additional groupings to emerge, if required.

Based on prior seminars of the same length, participants were asked to share one to three seminal readings in the HFI area that they thought everyone should know about (Benford et al., 2018). Participants were also asked beforehand to prepare an introductory talk in a Pecha Kucha style format. They were invited to explain their choice of the seminal readings, present their prior HFI work in the area, and what they thought the grand challenges were, based on the hurdles they had faced in their own work so far. Potential grand challenges that emerged through discussion were noted for consideration. These notes were loosely grouped based on the prior categories mentioned above, which were later collaboratively and iteratively refined by combining similar individual challenges into broader grand challenges.

Following this first collection and grouping effort, a longer activity period (half-day) was allocated to articulate the individual grand challenges within each grouping in more precise terms. Participants then worked within self-selected teams to refine the individual wordings, encouraged by the organizers to also articulate how these challenges are

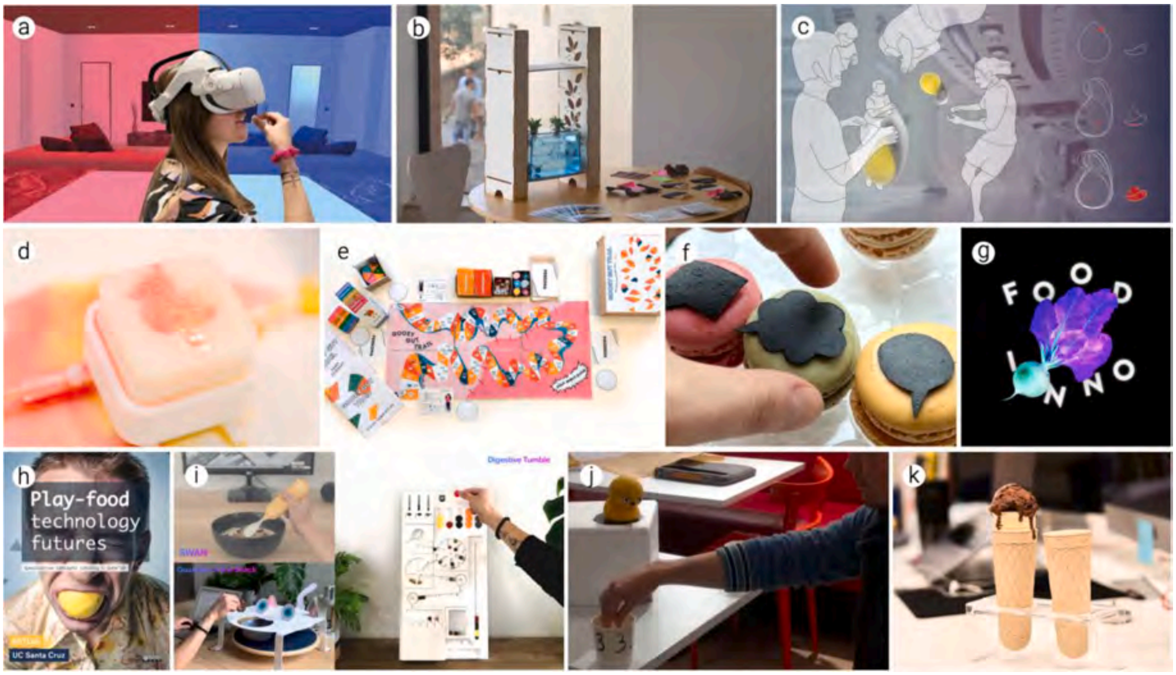

Fig. 1. A collage of HFI works: (a) "Virtual Tasty": exploring VR and food; (b) Desktop hydroponic garden; (c) Space food experiences; (d) "Logic Bonbon": food as computational artifact; (e) Board game teaching gut interactions; (f) Edible capacitive sensor; (g) Cover of FoodInno 2019; (h) Speculative catalog of play-food technology futures; (i) Playful tangibles to explore food interactions; (j) Artificial commensal companion; (k) "iScream": playful gustosonic ice cream experiences.

specific to HFI. Results were documented, collated, and then discussed together again with the entire group in order to resolve any instances where one grand challenge was grouped under more than one category. Such multi-assignments were rather easily resolved; however, the names of the groupings were heavily debated. For example, everyone agreed on "technology," but the "user" category was discussed extensively as it appeared to overlap with design. Similarly, "society" was discussed in terms of whether or not it had the right name at all. Also contentious was the "design" category, as it seemingly had unintentionally turned into a catch-all for grand challenges that did not fit elsewhere. Another debated category was "other", which was briefly named "sustainable design" before its grand challenges were moved under "ethics". The associated discussions helped identify additional challenges that we added and also aided in refining existing ones. The discussions also clarified whether some of them can indeed be considered "grand" or whether they are important, but not elementary for the future of HFI to be solved. Critical voices also emerged, questioning whether some of the challenges were not specific enough for HFI but rather apply to HCI or even technology projects more broadly. Furthermore, it was questioned whether some of the proposed challenges are so big that they are outside the scope of HFI or cannot be solved by HFI, in particular those that were concerned with sustainability and associated supply chains.

To support these discussions from a different angle, an interactivity-style session was designed for participants to exhibit, discuss and review their own HFI work. This included sensor-equipped eyeglasses to detect chewing activity and an interactive drinking utensil that influences taste perception through weight distribution. Experiencing these systems not only appeared to enrich participants' enjoyment of the seminar, but also generated discussions about how systems development and grand challenges inform each other.

In order to further refine the grand challenges, we also conducted a peer-review session in which the different teams from the grouping exercise reviewed each other's results, respectively. Participants were also encouraged to comment on, add and edit any content within the associated documents as they saw fit. This resulted in what we considered a more structured set of challenges that were articulated more uniformly, bringing them more in line with one another. Following on from these activities, participants were asked to engage in an exercise that aimed to help refine the challenges by speculating what the field of HFI would look like in the year 2052. "How would the future of HFI look like if we do not solve those grand challenges?" was the driving question of this speculative design session (Dunne and Raby, 2013). This approach was used to collectively imagine "possible, probable, plausible, and preferable futures". We encouraged participants to also consider sustainable and equitable futures using an extended "flashlight" visualization (Fig. 2) (Dunne and Raby, 2013).

Additionally, participants were instructed to imagine what a newspaper article would look like that responds to this speculation, which was to be supplemented by a speculative social media Tweet. This speculative media snippet exercise was designed to help think more concretely about the grand challenges and their implications.

A second peer-review session aimed to critically examine the refined challenges and arrive at a more textual representation. The results were again documented in an online document and shared with the entire group to elicit feedback. As part of this session, we also presented participants with the "SPRUCE" framework (De Freitas et al., 2021) (as we previously had good experiences using it in our practice) – originally developed to create a desirable future using responsible design through providing a practically-oriented structure – in order to help reflect upon HFI from a responsible design perspective. Participants appeared to embrace this opportunity and consequently developed a new "SPROUT"

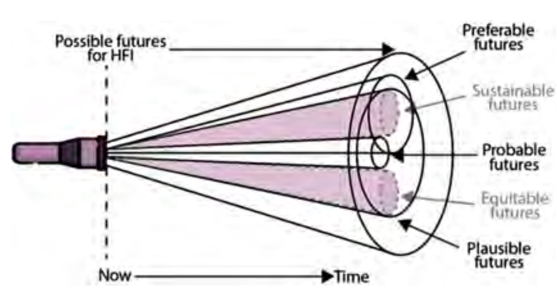

Fig. 2. Flashlight visualization used in the speculative design session.

framework that unites a vision of promoting Safe, Personalized, Responsible, Original, Uniform, and Transformational HFI futures (explained later in our “towards a shared HFI future” section).

What followed was an iterative and reflective discussion and writing session, both in individual and whole-cohort sessions, to ensure the integration of all the results from the different activities. On the pre-final day, an interactive session was organized to act out via role-playing further thoughts on the possible consequences we face in the future if the grand challenges are not to be solved. Participants played out an overreliance on cooking robots producing anti-social behaviors, the concept of food distribution based on “social credit” criteria, and many more. This was followed by a “thinking through writing” activity. Here, participants were encouraged to collaboratively (Tomlinson et al., 2012) develop the textual representation for each challenge and review it while it was emerging, including considering which challenge was so important that it could not be excluded for brevity purposes.

The final activity involved collating all the results and discussing them in a townhall-style setup in order to ensure that nothing important had been missed. Reflections were then facilitated through the presentation of three final questions everyone should think about, which were suggested to begin with “I like …”, “I wish …”, and “I wonder …” (Stanford d.school, 2018). These questions aimed to facilitate reflection on what was achieved but also what could be improved upon in the future.

The result of the seminar was an articulation of 10 grand challenges across 4 categories (technology, users, design and ethics), which we now describe.

4. Grand challenges in HFI: technology

The “technology” category encompasses challenges regarding the technical implementation or materialization of new forms of interactivity with/through food and food practices. The challenges under the “technology” category are: sensing taste, synthesizing food and food as interaction material (with 3 stages: embedding interactivity in food utensils, embedding interactivity components in food, and edible interactivity).

4.1. Sensing taste

When we refer to taste here, we mean the special sense that perceives and distinguishes the sweet, sour, bitter, salty, or umami quality of a dissolved substance, usually mediated by taste buds on the tongue, but here captured through a sensing system. This is because if HFI is aiming to enhance and enrich the eating experience, where taste plays a major role, we believe that it might be beneficial to be able to sense the sweet, sour, bitter, salty, or umami quality of a food item in order to feed this information into an interactive system. Interaction designers have a wide range of microphones available to sense sound, ranging from cheap models for quick-and-dirty prototyping, to expensive high-end versions for production-level installations. Similarly, there is a wide range of cameras available for interaction designers to experiment with. However, when it comes to taste, there are not many sensors available for the HFI researcher in the same way that other sensors are available on many of the popular HCI prototyping websites like Sparkfun.

In recent years, however, progress has been made, for example, “digital tongue” systems have been developed that can deconstruct selected components within certain dishes (Fuentes et al., 2021). Electrical impedance spectroscopy has also been used for food characterization (Grossi and Riccò, 2017). Such advances, in particular when combined with systems that interaction designers are familiar with like Arduinos (Corbellini and Vallan, 2014), could be very useful for future HFI research. In particular, we would welcome more technological advances that would allow feeding the data in real-time into an interactive system. We believe that this could help when aiming to design HFI systems that benefit from being able to sense taste.

4.2. Synthesizing food

A dish most often comprises of multiple ingredients that the chef expertly puts together. Many HFI systems would benefit from the ability to computationally synthesize food, however, how to do this is still an unsolved challenge.

Although large collections of recipes already exist online from which an HFI system could draw from, and electrical devices are available that can aid in preparing the making of a dish (such as the “thermomix” (Thermomix, 2022) that displays a recipe on an LED display and provides instructions in which order to add the ingredients before automatically cooking them), as well as robots that can automate the cooking process (Park et al., 2017), they are still very limited in their abilities. For example, current systems are not able to adapt to, for example, alternative ingredients that require altering their procedures such as when an egg is smaller than required. Furthermore, these devices are only able to mix ingredients, whereas fabrication devices such as 3D-printers that can handle food produce are able to create entire dishes from scratch; however, an integration of these technologies to synthesize more complex dishes is still underdeveloped. Ongoing research is investigating the possibility to synthesize more complex dishes, for example, researchers have been able to synthesize very particular food textures (Pereira et al., 2021) and managed to create food that can change its state after printing (Navaf et al., 2022). However, such more advanced systems suffer from the same limitations as additive manufacturing (Baudisch and Mueller, 2017), but are exacerbated as a result of using food as printing material (Khot et al., 2015, 2015b, 2020; Khot et al., 2017a; Khot et al., 2017b). For example, most food 3D-printers can only dispense a small amount and a limited range of materials, not suiting common recipes. Furthermore, most personal fabrication devices are not very good at changing their process on the fly, giving users only limited interaction opportunities throughout the process (contrasting how, for example, chefs continuously check the taste of a dish in progress). Additionally, only a very limited set of foodstuff is suitable to be used in today’s personal fabrication devices, limiting the range of dishes that can be computationally synthesized. Subtractive fabrication devices, such as laser cutters, appear to have the potential to help with synthesizing food, however, they have their own problems: for example, laser cutters create temperatures that alter the taste of many ingredients.

One way to address this challenge is to combine fabrication devices, allowing for, for example, mixing and cutting within one process pipeline. Furthermore, applying temperature changes, such as heating up or freezing, within the same process pipeline could help address this challenge, as it would allow to create even more dishes. However, how to combine such devices while ensuring that safety standards are upheld (for example, keeping food-safe temperatures during fabrication processes that depend on warming the material to make it digitally dispensable) is still unclear. Furthermore, how to ensure that the pipeline does not alter the taste in an undesired way (for example, when 3D-printing takes longer than the cooking process demands) is also not yet fully understood. In addition, how to combine fabrication with cooking’s chemical processes (such as the Maillard reaction) into one coherent synthesizing pipeline is also still unclear. Lastly, current fabrication devices commonly benefit from a technical person being able to oversee the process to engage with low level details in case of malfunction, for tuning and maintenance. It remains a challenge to develop user-friendly devices that do not require such technical support to easily specify the properties of the desired food to be synthesized, not only in geometry and aroma, but also in color, texture, and taste.

4.3. Food as interaction material

HFI systems are concerned with interactions where the user eats, meaning that an essential physical element of the interaction is present at the beginning of the interaction, but then gone, ending in the user’s stomach. As such, food is HFI's "material concern for interaction" (Wiberg, 2018). Food does not only have physical characteristics quite different to most other, more traditional, HCI materials of computational devices (soft, malleable, liquid, etc.), but it is also consumable and ideally palatable, hence a challenge for HFI is how food can be an interaction material.

We point out that prior work already remarked that computational devices appear to become closer and closer to the human body, with many people now comfortably donning wearables (Mueller et al., 2018). However, HFI needs to go a step further and hence "closer", considering that people put food *inside* their bodies. This could lead to developments where participants eat computational devices. This might not be as strange as it initially appears. For example, we point to modern thermometers that people already put in their mouths, or tiny sensors in capsule format that participants swallow, resulting in "ingestibles" (Li et al., 2020a, 2020b, Li et al., 2021a, 2021b, 2023; Li et al., 2019). However, *eating* computational devices faces additional challenges, going beyond the safety concerns already raised with ingestibles: for example, users might bite on a device, not only breaking its functionality but possibly also releasing toxic components. Furthermore, the stomach's acids might damage the device and affect its form in a way that remaining bits might get stuck inside the participant, creating a hazard that needs to be surgically removed.

We find that, so far, HFI appears not to have engaged much with such a view on food as interaction material, but rather physically put existing interactive devices around food (Deng et al., 2022). To aid future work in this area, we now describe three key stages along with a timeline through which this challenge could be addressed. The first stage is concerned with embedding interactivity in food utensils, the second stage with embedding interactivity components in food and the third stage with edible interactivity (Fig. 3).

4.3.1. Embedding interactivity in food utensils

This is probably the easiest stage to implement and hence designers interested in HFI might want to start here. Several examples exist where designers embedded traditional interactivity components, such as sensors and actuators, into food utensils like crockery (Wang et al., 2018). For example, Wang et al. embedded a capacitance sensor and a loudspeaker into an ice cream cone to enable an interactive ice cream experience (Wang et al., 2019a, 2019b). Similarly, the "SWAN" system (Khot et al., 2020) uses computer vision to detect if people eat mindlessly in front of a screen and uses a motor inside a spoon to take control of the associated eating actions to foster mindful eating. Relatedly, Mitsudo (2016) embedded a sensor into cutlery to sense when people eat. Another example is the interactive service set with a sensor inside the plate to enable an interactive eating game for children (Joi et al., 2016). There is also an interactive cup with a straw that senses if someone drinks out of it and plays a sound in response to facilitate an enriched drinking experience (Wang et al., 2020b; Wang et al., 2021, 2022). Another example is the "straw-like user interface" project that presented a cup that allows diners to virtually experience the sensations of drinking with a straw. The sensations were created through the use of an embedded speaker, servomotor, and solenoid, based on pressure, vibration, and sound data recorded during drinking with a straw (Hashimoto et al., 2008, 2006, 2005).

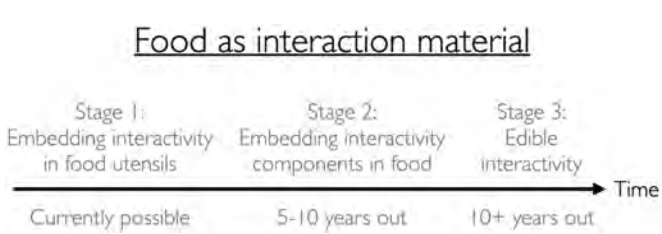

Fig. 3. Three stages and their timeline of food as interaction material.

These systems suggest that embedding interactivity in food utensils is feasible and can cover a wide range of dining scenarios. Furthermore, the required interactivity components can often be sourced from existing HCI approaches, such as tangible computing or ubiquitous computing, where documentation, software libraries and toolkits often already exist, speeding up implementation efforts. However, systems in this first stage suffer from a missing integration (Mueller et al., 2020, 2023b,a; Mueller et al., 2022;Semertzidis et al., 2021, 2022; Andres et al., 2022) with the food material itself: they mostly sense eating actions by embedding sensors into the food utensils with which people eat. As a result, they "work" even if the user does not consume the food, as long as they perform the movements that lead to eating. Therefore, augmentation of the movement affects the eating experience, not augmentation of the eating itself. In response, we point to the next two stages, beginning with "embedding interactivity components in food".

4.3.2. Embedding interactivity components in food

The second stage concerns embedding interactivity components in food. As computers are becoming smaller and smaller, it seems reasonable to expect that interactivity components could become so small that they could be embedded into the food itself, allowing users to ingest them as part of a dish. Recent research explorations suggest that this envisioning is increasingly becoming plausible in about 5–10 years. For example, prior work investigated a "gum sensor" that senses actions while being in the mouth (Darabi et al., 2015). Similarly, Li et al. presented an ingestible sensor that can wirelessly sense temperature in the user's intestines, allowing participants to affect their intestine's temperature by consuming different foods and drinks (hot or cold) (Li et al., 2018, 2018). Although these devices cannot be digested along with existing dishes (as users might bite on them), they hint at a future where designers could embed interactive components in food in order to support interactivity not just when the user picks up a particular food item with their food utensil, but also in the user's mouth and possible even in their digestive system. With this, unlike in stage 1, the interactivity would only unfold if the user actually ate. This not only prevents "cheating" actions to occur, but also offers novel opportunities afforded by the food, in particular, we point to the fact that food undergoes a transformation process in the user's mouth (chewing, swallowing) and digestive system. For example, we can envision future HFI systems that track food intake by sensing chewing actions and only offering interactivity when the user has swallowed the food. This could be useful in nursing home settings where staff need to ensure that (bulimia) patients have eaten their meals. We can also envision future HFI systems that only unfold their interactivity when in the user's mouth or in their intestine. This could create novel entertainment experiences, reminding us of Pop Rock Candy that has pressurized carbon dioxide gas bubbles embedded inside, creating a popping reaction when in the mouth.

Overall, we would argue that, in this stage, any interactivity components are more tightly integrated with the food due to their physical size allowing it to be embedded inside the foodstuff, with the participant (possibly unknowingly) eating an interactive system through their dish. This, of course, raises ethical questions, such as whether the user should always know what they eat. See, for example, restaurants stating ingredients on their menus in order to cater to food allergies and governments requiring food makers to print ingredient labels on their products in order to support transparency. However, these existing approaches might not be sufficient in stage 2, as the interactivity could only unfold in the user's mouth, making the experience a very personal one as a result of a dynamic feedback loop. Another challenge is concerned with the size and taste of the interactivity components, as they might be so small that they can be eaten, however, they might change the mouthfeel, flavor, taste etc. of the dish, affecting the overall experience in a way that the food designer had not intended. In response, we point to the 3rd stage.

4.3.3. Edible interactivity

The third stage is concerned with edible interactivity, meaning that here, the food itself is interactive, rather than accompanying (1st stage) or housing (2nd stage) interactivity. This stage is probably the most ambitious and hence the furthest out in terms of implementation realization, however, we believe that it holds great potential without the compromises associated with stage 1 and 2 systems.

Interactivity components today are not edible, making stage 3 systems difficult to envision, yet alone develop. However, advances in material science have resulted in research projects that showed that basic electrical components are feasible to produce using edible material. For example, recent research developed a number of edible electronic devices including a pH sensor, radio frequency filter, and a microphone (Xu et al., 2017). Furthermore, researchers have demonstrated that capacitive sensors can be made out of food materials such as charcoal (Marion Koelle et al., 2022) and supercapacitors out of seaweed, Gatorade and sliced cheese (Wang et al., 2016). These efforts aimed at demonstrating that existing electrical components could be produced with sustainable materials. We note that due to the focus on sustainability, palatability was probably not of highest importance. However, the results suggest that edible electronics are possible. We are inspired by this prior work and believe that food could be produced at a complexity level that enables at least simple computation while offering a palatable experience. To further fuel such investigations, we also point to research that was inspired by "alternative ways for computation" (Adamatzky, 2021) that suggested liquid-based computational systems. The result is a palatable "cyber bonbon" that can compute either an AND, OR, or XOR logic operation through differently flavored coulis liquids that the diner presses through the dessert via small pipettes (Deng et al., 2022). The (albeit simple) interactivity enabled by the logic gate allowed the cyber bonbon to change its flavor while also providing visual feedback in the form of a liquid-filled display. We can regard this system as an initial attempt towards edible interactivity, as the gate that enabled the interactivity was edible, starting the possibility to investigate what "computation" might taste like (Deng et al., 2022).

We see this third stage analogous to the early days of computing, where cumbersome and bulky hardware devices were only able to perform simple computational functions (like the logic gates above). However, with technological advances and miniaturization, more complex functionality became possible, enabling highly advanced computational systems as we know them today. Similarly, we can envision complex interactivity systems in the future that are completely edible. This would allow for novel systems previously not possible, enabling users to experience what interactivity tastes like. Such systems could perform interactivity inside the user's body without the food designer making any compromises such as in stage 2 above. Furthermore, the interactivity could respond to chewing input in a way that transforms the entire taste of the dish, as the dish itself performs the interactivity (as suggested by material science research (Souto et al., 2022)). Moreover, the dish could perform interactivity inside the user's digestive system without the same health concerns as with the ingestibles above (Li et al., 2018, 2018). Through this tight integration of interactivity with food, a more holistic HFI vision could be facilitated that does not suffer any of the limitations in the previous stages. However, we point out that the material properties of current computational devices like the silicon in microchips have enabled rapid advances such as postulated by Moore's Law (Schaller, 1997). In contrast, efforts such as with the fluid-based gates appear to have much bigger limitations as a result of the laws of physics: for example, the coulis liquid is limited in terms of the speed at which it can travel, and the tubes housing the liquid can only be reduced to a certain size without the coulis liquid getting stuck (Deng et al., 2022). As such, we believe that stage 3 will be constrained by the laws of physics probably more than we encountered with traditional interactive systems. This would make advancements around stage 3 systems slower to emerge and hence we will probably see associated systems mostly along a timeline that is 10 and more years out. These constraints speak to an article on grand challenges in immersive analytics that similarly laments that "overcoming constraints of reality" is one of the key hurdles for the field to overcome (Ens et al., 2021).

5. Grand challenges in HFI: users

The "users" category encompasses challenges arising from our understanding of the users of HFI systems. The challenges under "users" are: supporting creative food practitioners and evaluation frameworks for HFI.

5.1. Supporting creative food practitioners

Many HFI systems are best used by food designers such as chefs and restaurateurs as they can employ them to elevate their creative practice. For example, the projection-mapping system (Hagger, 2018) allows chefs to enrich the dining experience with animated content that can be programmed to highlight where the ingredients originally came from. However, most chefs do not have an interaction design background and hence might not be competent with the hard- and software. Prior HCI work has already investigated how to support non-expert users (Cheng et al., 2019), however, supporting creative food practitioners brings about new, far more complex interaction challenges.

Consulting interaction designers can provide the initial setup. However, as menus are often adapted to respond to the availability of local produce, creative food practitioners need to be able to adjust the interactivity component based on the food that they are serving, all while considering the guests they are hosting. This could accommodate, for example, a birthday or food allergies. For this, interfaces need to be designed that are not only operable by creative food practitioners with little training while supporting frequent reconfigurations but also support the fast workflow in a kitchen and restaurant. For example, a chef ready to serve a hot dish does not have time to wait for an update to be installed. Furthermore, the interface design needs to consider that the creative food practitioner might have both hands busy or that they are not clean, all while working in a loud kitchen, making some popular interaction modalities such as touch and voice input impractical. Additionally, as kitchens often house an entire team that might all need to interact with an HFI system, these different users need to be managed without requiring complex and time-consuming logging-in processes while allowing the head chef final say over the resulting dish.

To solve this challenge, future systems might need to offer low entry barriers into HFI interactions, for example, by providing users with multiple input devices to achieve a goal. However, with such a solution, the creative food practitioner needs to be able to quickly discover what input possibilities are available to them (Norman, 2010), while possibly also demanding additional cognitive load in an already hectic environment. Working towards a unified interaction vocabulary could help in an effort to support creative food practitioners so as not to distract them from their creative craft with unsuitable interfaces.

5.2. Evaluation frameworks for HFI

Evaluating interactive systems with the aim of drawing conclusions is difficult under the best of conditions. In HFI research, there are specific challenges: these include the novelty effect (Koch et al., 2018; Shavitt and Stellner, 2011; Shin et al., 2019), which has a rich history with food innovations that have often been initially dismissed as "gimmick" but turned into stable food experiences. In particular, when it comes to so-called "fads", research doubts the view that benefits people perceive through novelty are not valuable (Shavitt and Stellner, 2011). In fact, most technologies go through a "diffusion of innovation", where "early adopters", who are often younger people (and today's diners match this young demographic in many countries: 40 % are born after 1996 (Wood, 2019)), drive the initial uptake by a majority later (Rogers et al., 2014). Furthermore, there is a long culinary history of food innovations that stood the test of time. For example, "alphabet soup" was in 1900 considered a "novelty", yet it is still going strong (Edwards, 2014). It is the hope that HFI can lead to similar success stories.

Being able to evaluate the effects of certain HFI systems is crucial in understanding their value, but what are the most suitable methods and metrics to quantify these effects? How do we deal with the curse of dimensionality in these studies, given the wide range of factors to assess in these complex systems? We propose that the HFI research community needs to develop evaluation frameworks that clearly specify what aspects of HFI systems are assessed and how these can be measured using suitable metrics. Such frameworks could include measures that capture the nutritional value of the foodstuff; for this, the framework will need to learn from other fields, such as nutritional science. The frameworks might also need to consider personal food preferences and food allergies. There might be a benefit for HFI having multiple frameworks for different evaluations based on different requirements. Prior HCI frameworks on context-aware computing (Abowd et al., 1999) might be useful here, as they already aimed to help consider wider aspects of an experience, however, how this context can be sensed for such evaluation frameworks is still unknown.

While the specifics of evaluation techniques and metrics may vary depending on dining scenarios and systems, a variety of evaluation frameworks might offer a starting point for study design that may enable comparisons across studies. Such frameworks may also provide perspectives on when specific research questions benefit from a more focused, controlled in-the-lab study and when an in-the-wild (Rogers, 2011) study in a restaurant, canteen, or food outlet might be more suitable.

6. Grand challenges in HFI: design

The "design" category encompasses challenges regarding the design of HFI experiences. The challenges under "design" are: dealing with the taste experience's complexity, identifying interactivity opportunities in food scenarios and designing new forms of commensality.

6.1. Dealing with the taste experience's complexity

The taste experience is a highly complex (Petrini, 2003) and hence any interaction concerned with it will need to deal with its inherently rich and multimodal complexity. A person's taste experience is influenced by a wide variety of factors that can be affected through interactive technology (some to a higher degree than others), including smell, mouthfeel, the sound the food makes when biting (Spence, 2017), but also the environmental noise (Spence et al., 2014), the company in which one is eating (Herman and Polivy, 2008), and even the weight of the eating utensil (Harrar and Spence, 2013). In consequence, designers can use a variety of systems to enhance or dampen the taste experience, for example by using speakers to play different sounds (Wang et al., 2020a) or fabricate an alternative structure for food so that it sounds different when eaten (Souto et al., 2022). For this, designers have a wide variety of different sensors and actuators at their disposal (IMUs, cameras, microphones, etc.) and options where to place them (speakers in cutlery, actuators in eating utensils, 3D-food printers to produce different food structures, etc.). However, it is still unclear what the best approach is, in fact, the best solution will probably need to consider a combination of interfaces to address the taste experience's complexity. Prototyping such combinations is difficult (Perelman et al., 2016), making a systematic investigation into which modality provides the "best bang for the buck" challenging. For example, if an HFI system distributes the weight of an eating utensil in a way that makes the perceived taste experience more bitter, will a "sweetness" induced sound that is played at the same time cancel the weight distribution out? Understanding the relationship between different effects as a result of different interactivity components will allow HFI systems to better exploit the richness of taste experiences.

6.2. Identifying interactivity opportunities in food scenarios

Prior surveys in HFI highlighted that there are several food scenarios where interactivity could be not only beneficial but also welcomed (Altarriba Bertran, Jhaveri, et al., 2019; Bertran et al., 2018; Bertran et al., 2019, 2019). For example, Wang et al. showed that adding interactivity can be welcomed in casual ice cream-eating scenarios (Wang et al., 2020a). However, our discussions with culinary experts suggest that adding interactivity to food scenarios is not always welcomed. For example, these conversations, including with some of the world's best chefs, revealed that they can see their food creations as creative outputs that should be eaten in a particular way, and only in that way. The suggestion to introduce interactivity in order to provide the diner with more control over what and how they eat can be quickly regarded as compromising the chef's integrity. For example, some restaurants refuse to cook a steak beyond medium, even if the diner explicitly expresses the wish to do so.

This tension between the chef's integrity and the diner's possible desires, including the argument that it is the diner who is ultimately paying for the experience, raises interesting questions around the role of interactivity within this relationship. After all, interactivity usually assumes a high sense of agency in the user (Mueller et al., 2021): without the diner having some agency, the envisioned food scenario is more akin to a movie, where the diner passively consumes the chef's creation. On the other end of the spectrum sit possible experiences more akin to action games, where the diner has a lot of agency as they are able to control at any point in time what and how they eat. We can see that such high-agency dining experiences are probably more suitable to budget food scenarios or casual eating/drinking settings, such as prior work around adding interactivity to casual drinks settings via an interactive drinking vessel suggests (Wang et al., 2021; Khot et al., 2014, 2015a, 2015b). In other eating scenarios, such as when a high throughput is required, like in some canteens, introducing interactivity might be similarly unsuitable as the technology might extend the duration the user spends at the eating table.

Therefore, we highlight that for HFI a grand challenge is to identify interactivity opportunities in food scenarios. For this, the research community and diners need to work together in order to be able to answer questions such as: Why do specific food scenarios benefit from HFI systems while others do not? What are the key characteristics of specific food scenarios that make HFI systems useful? When in the overall food experience is it best to integrate an HFI system?

By creating a set of recommendations for when HFI can benefit a particular food scenario, researchers could help the hospitality industry to use HFI (more) successfully. Determining the scenarios that HFI systems can enrich could facilitate engagement of diners in the creation and use of such systems, allowing for user-centered design advancements. Such advancements could scaffold conversations and design processes that holistically tailor HFI solutions to the characteristics of a particular food scenario. This could lead to a greater adoption of HFI systems that maximize benefits to users.

6.3. Designing new forms of commensality

Humans do not only need food for its nutritional values: food is inherently social and eating with others, i.e., commensality, caters to the human need for connectedness and belonging (Ceccaldi et al., 2020). In fact, the link between food and social relationships is so strong that food can become a social surrogate, an object that acts as a reminder of a past, positive social encounter (Troisi and Wright, 2017). Food can therefore create a sense of belonging in situations of loneliness (Troisi et al., 2015), thus becoming "comfort food" (Spence, 2017). However, modern lifestyles are putting commensality at stake, with single-person households becoming predominant worldwide, with people finding themselves in situations of loneliness (US Census Bureau, 2018, 2022). Along with such phenomena comes the urgent need to bring commensality back for participants who are physically distant. For example, HFI research could develop solutions to share meals online (Barden et al., 2012). HFI research could also develop artificial commensal companions for people living alone (Mancini et al., 2020). In fact, research shows that merely watching videos of other people eating (known as Mukbang Choe 2019) can give a glimpse of a sense of sharedness compared to people eating alone. When participants share meals online through, for example, video-conferencing systems, they do it for the same reasons they do it face-to-face: because commensality "adds something" to their social encounters, making them feel less alone, and closer to their commensal partners (Ceccaldi et al., 2020). However, when such video-conferencing systems are evaluated by users, they are rated to be unable to provide experiences that actually cater to participants' needs. In other words, although distributed commensality systems can be implemented technically (Barden et al., 2012), they still not provide fully satisfactory commensal experiences. From this point of view, HFI can contribute to creating new commensal opportunities, endowing technologies with the possibility to share taste and smell while providing new ways to enjoy food and eating-related activities while also taking the social side into account (see, e.g., Fig. 4). Although interactive technology can foster commensality in several different ways, we hereby describe two digital commensality scenarios that can exemplify how technology could "join the dining table": remote dining and artificial commensal companions.

6.3.1. *Remote dining*

Technology already allows videoconferencing with a remote friend or relative while eating (Spence, 2017). There are also more elaborate tele-dining installations that allow for some element of interactivity with those whom we may be dining with remotely (e.g., Barden et al. 2012).

Existing studies reported participants' responses to questions checking the major shortcomings of currently available remote dining experiences. For example, in work by Ceccaldi et al. (2020) 37 % of participants reported the impossibility of sharing food, taste, and smell; 29 % felt observed as they were eating; 25 % reported problems with the device or with their internet connection. So, as part of this grand challenge, efforts will need to go toward technologies for sharing meals online, allowing co-diners to experience the benefits (e.g., a sense of togetherness and belonging, improving well-being and quality of life) that characterize face-to-face commensal settings. Smell detection and food 3D-printing (Mueller et al., 2020) (see also "technology" category)

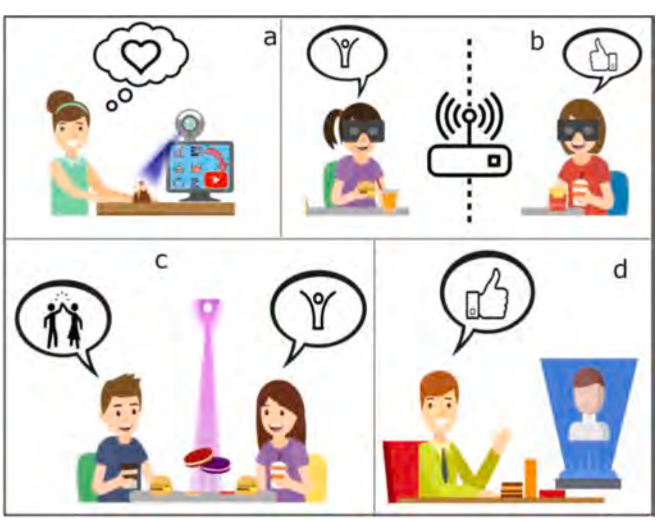

Fig. 4. New forms of digital commensality: (a) adding previously captured eating activities to existing HFI experiences; (b) adding a digital layer to commensal interactions, allowing remote users to share a meal online; (c) enhancing the eating experience through, e.g., projections or augmented reality; (d) synthesizing artificial dining companions (Arza et al., 2018).

are only two examples of how novel technologies could be embedded in future tools for remote dining to overcome its current limitations.

6.3.2. *Artificial commensal companions*

Technologies such as social robots, virtual agents, or chatbots can be used to enable and enhance social interactions and conviviality, and, consequently, increase personal well-being. In 2020, Mancini et al. (2020) introduced such a social companion for eating in the form of a robot producing simple non-verbal signals while the user is eating. Results from a qualitative survey indicate that the presence of the social robot is preferred over eating alone. However, many questions in the area of artificial commensal partners are still unanswered, for example: can such technologies make the eating experience more enjoyable, and will it increase the conviviality at the table? (Mehta et al., 2018).

7. Grand challenges in HFI: ethics

The "ethics" category encompasses challenges regarding ethical HFI research. The challenges under "ethics" are: HFI *for* and *as* sustainable practice and applying HFI ethically.

7.1. *HFI for and as sustainable practice*

Sustainability is an epic challenge and HCI is increasingly interested in fostering sustainable practices (Hansson et al., 2021). HFI as a field has a unique opportunity but also a big hurdle to overcome if it wants to contribute positively to sustainability efforts. Unlike prior HCI works that mostly concerned themselves with sustainability issues around power consumption and e-waste (Perkins et al., 2014), concerns around sustainability as challenge within the HFI field are heightened: HFI systems not only need to address power consumption and e-waste problems as discussed in traditional HCI (as they also contain electronic devices), but also food waste, as they are intimately connected with produce. The challenges are therefore: HFI *for* sustainable practice and HFI *as* sustainable practice.

7.1.1. *HFI for sustainable practice*

If HFI wants to grow into a mature field, it needs to take the issue of food waste seriously and demonstrate that its focus on food while utilizing the power of technology can contribute to sustainable practice. There are already HCI works that have used mobile phone apps to educate people about how to reduce food waste (Titiu, 2019) and there are augmented bins that aim to make people aware of the amount of food that they dispose of in order to promote more sustainable practices in the kitchen (Altarriba et al., 2017; Comber and Thieme, 2017). These approaches, although applaudable, are mostly concerned with advocating better food choices at the purchasing level in order to avoid buying food that will not be eaten and hence disposed of. In the future, however, we hope that HFI research is going a step further and help support sustainable practice closer to the eating experience itself. For example, fabrication systems could produce food on-the-fly so that there is no need to cook food "just in case" people will be very hungry. However, such systems face the challenge that in some communities providing an oversupply of food to guests is a common cultural practice (Phasha et al., 2020).

7.1.2. *HFI as sustainable practice*

HFI also faces the challenge of becoming a sustainable research practice itself. We refer to our design practice, where we noticed that a lot of food waste has been produced as part of our explorations in our labs. We believe that the field must become better at that. HCI research already faces sustainability challenges through its iterative methods where not only a lot of energy is consumed but prototypes also produce e-waste. HFI research adds to this by producing food waste during the prototyping stage (which is an essential part of many research-through-design methods (Holmquist, 2012) that a lot of HFI researchers seem to engage in). Furthermore, HFI researchers are missing clear guidance on when food is still safe to eat if being exposed to technical equipment, leading possibly to researchers acting on the side of caution and applying unnecessarily strict hygiene protocols that result in food waste. For example, chemical labs have clear guidance as to what constitutes contamination, but HCI researchers who want to set up an HFI lab face the challenge that there is not much guidance available (is food that got in touch with a microcontroller still ok to eat?).

7.2. Applying HFI ethically

Concerns over tracking and collecting personal user data are already prevalent with today's smartphones (Ketelaar and Van Balen, 2018). These concerns have the potential to become much more substantial with HFI systems, as they may provide access to more bodily and hence private data, such as data on what people eat, how, when, and with whom. For example, in the future, advanced sensors could detect how food is processed inside the user's body and even infer health conditions based on people's excretion. For example, see the speculative system installed at an HCI conference that pretended to be able to infer personal health data from attendees' bathroom usage through a sensor included in the venue's toilets (Fox et al., 2019)). Grocery shopping and food delivery apps already track what food people order. If a smart fridge is connected to this data, a system could infer how much food is actually being consumed, and in combination with a smart bin (Altarriba et al., 2017; Comber and Thieme, 2017), this could provide a detailed account of what people eat and when, and how much food waste they produce.

This increased collection of food-related data raises concerns. For instance, there could be misuse through health insurers who might raise their premiums if their customer is eating too much junk food. On the other hand, governments have a responsibility to support their citizen's health, and only through a multi-pronged approach that includes industry and individuals will we be able to address issues such as the obesity epidemic (Australian Bureau of Statistics, 2013). Having such detailed food-related data could be valuable when aiming to achieve this, hence a balance needs to be found that involves careful management of the data that prevents misuse. However, eating is highly socially contextual: for example, people in overweight social circles tend to eat more (Christakis and Fowler, 2007). Hence, individual data from within a social group could be more powerful to address obesity issues than larger population-wide aggregate data but might make the individual who produced the data identifiable. Shaming people for certain food purchases tracked through the systems is another potential misuse.

To address this challenge, we believe that users at least need to be made aware of what data is collected from them, however, as most people eat three times a day, there will be a lot of data that many users might find overwhelming to consent to or manage in a meaningful way. Furthermore, interventions such as the "MetaCookie" deliberately deceive the user by displaying a bigger cookie through augmented reality than the user actually eats, drawing on the psychological study that showed that seeing larger portion sizes can make people feel full quicker (Narumi et al., 2011). Here, the system uses a psychological "trick" to help people eat less, which might be in the interest of the diner, for example, when on a diet. However, if the diner becomes aware that they are being tricked, will they still feel full and continue to use the system?

8. Summary

We will now summarize our grand challenges in HFI together with a sample of individual limitations we discussed in a table form (Table 2).

9. Towards HFI futures that are both shared and heterogeneous

Identifying key grand challenges is only the beginning of bringing the community together and establish a shared understanding of what was done, what could be done, and what it means for those designing

Table 2
Grand challenges in HFI together with a sample of individual limitations we discussed.

Technology	Users	Design	Ethics
Sensing taste • Limited sensor capabilities • Limited integration with interaction designers' toolkits • Limited real-time support for interactivity	Supporting creative practitioners • Limited knowledge about food practitioners as system users • Limited knowledge of how to support creative practitioner's frequent reconfigurations in the kitchen • Limited knowledge of how to support the kitchen's fast workflow • Limited knowledge of multimodal input for creative practitioners • Limited knowledge of how systems need to be designed so as to not distract creative practitioners or demand too much cognitive load, distracting them from cooking	Dealing with the taste experience's complexity • Limited knowledge of how to design for taste's rich and multimodal complexity • Limited knowledge of how to combine interfaces in order to address the taste experience's complexity • Limited knowledge of how to design for the taste experience's individual aspects that affect each other	HFI *for* and *as* sustainable practice • Limited understanding of how fabrication systems could support food production on-the-fly in order to facilitate sustainable practices • Limited knowledge of how to reduce e-waste during research-through-design practice
Synthesizing food • Limited system capabilities to computationally synthesize food • Limited ability by food processing systems to adapt to changes in ingredients • Limited ability to synthesize complex dishes • Limited abilities to change synthesization on the fly • Current fabrication devices often create temperatures not suitable for food • Limited ability to synthesize beyond geometry and aroma • Fabrication devices still complex to operate	Evaluation frameworks for HFI • How to evaluate novel "gimmicky"- food systems • Limited knowledge what needs to be assessed • Limited knowledge about suitable metrics • Limited knowledge about what evaluation framework for what purpose	Identifying interactivity opportunities in food scenarios • Limited knowledge of where interactivity is not welcomed • Limited knowledge of how to maintain the chef's integrity • Limited knowledge of how to design the right agency split between diner and chef • Limited knowledge of how to design for high throughput • Limited knowledge of how to identify the	Applying HFI ethically • Limited knowledge of how to preserve user's privacy • Limited knowledge of how to prevent shaming • Limited knowledge of how people will feel when an HFI system tricks them in eating healthier

(*continued on next page*)

Table 2 (*continued*)

Technology	Users	Design	Ethics
		best time in the food experience to integrate an HFI system	
Food as interaction material • If food becomes an interaction material, danger arise as a result of eating toxic material like batteries • Systems work even if food is not eaten • Limited knowledge how to embed interactivity in food utensils • Limited knowledge how to embed interactivity components in food • Limited knowledge how to create edible interactivity		Designing new forms of commensality • Limited knowledge of how to design share meals online • Limited knowledge of how to design artificial commensal companions • Limited knowledge of how design affects conviviality	

HFI. Our grand challenges go beyond the pure idea of how technology affects HFI experiences but does acknowledge its wider relevance for society and global efforts toward sustainability. In an attempt to further foster this foundation, we now also present here the outcome from the group's reflection on responsible design, which was part of our process. Modeled based on the SPRUCE framework for responsible design (De Freitas et al., 2021), we developed the SPROUT framework to further foster a responsible HFI future. SPROUT calls for an HFI future that is:

Safe: HFI does not harm others or put others at unreasonable risk of harm (e.g., hygiene, allergies, eating disorders, use of pesticides/ antibiotics, etc.).
Personalized: HFI respects personal sensory, socio-economical needs and abilities, food preferences, and cultural diversity in terms of food choices.
Responsible: HFI is based on ethical, moral, fair, and sustainable practices (e.g., circularity, labor, production/location, use of natural resources/supply chain, etc.) through traceability and transparency of information.
Original: HFI is original in its outcome (food we are presented with and eat) and the process of food production and preparation (e.g., supply chains, manufacturing, food 3D-printing) through appreciating the importance of time (e.g., aging, seasoning).
Uniform: HFI enables reliable, consistent, inclusive skills development (like following a recipe) through capitalizing digital skills (e.g., multimedia, extended reality) and reduces boundaries through open access HFI and associated knowledge. This includes the democratization of the process of cooking and the use of ingredients from different parts of the world, which would otherwise not be accessible due to geographical constraints or lack of knowledge.
Transformational: HFI is to support transformation towards reaching strategic global goals (e.g., global societal problems such as food waste), but also to new food systems, habits, behaviors, and attitudes to improve acceptability and adoption. Change takes time, and HFI needs to facilitate that change.

Overall, HFI needs to respect time as a design feature, both for improving the quality of food through waiting or speeding up the production and preparation process without altering the quality and authenticity of the food. Dealing with contradictory concepts such as fast- versus slow-food movements, varying socio-cultural, socio-economic conditions and individual preferences, will long challenge HFI futures. Yet, it is a dialogue between all involved stakeholders that will enable a future of HFI we like to experience.

10. Limitations & future work

It is important to recognize the limitations and in particular the dangers of the HFI field, our participants pointed out (Obrist et al., 2018). In prior interaction design work on proxemic interactions, researchers have used "dark patterns" (Greenberg et al., 2014) – application scenarios where users are deliberately deceived through a particular technology – to articulate how a sub-field of HCI can easily turn "dark". We encourage future work to investigate such "dark patterns" in HFI to identify if and how similar scenarios might occur in the HFI field (such as we hinted at with our "applying HFI ethically" grand challenge) while hoping that our article presented here could be useful to structure such investigations.

We point out that our approach of conducting a seminar with experts has not only advantages but can also have a certain bias towards the assembling of the challenges. For example, we acknowledge that our experts were eager to drive the HFI field forward and hence might be optimistic about the broader social acceptability of the coming together of interactive technology and food. However, surveys amongst new generations suggest that diners are increasingly comfortable, and even eager, to use interactive technology as part of their eating experience, suggesting that expecting social acceptability will increase could be warranted. For example, surveys found that 73 % of diners believe that technology can improve the guest experience (Toast, 2017). Furthermore, 69 % of millennials (who eat out 20 % more than other age groups) do not expect just good food, but an experience that "stands out" (Yurieeff, 2018). In response, in surveys, 56 % of restaurateurs reported that they think that technology engagement is crucial (Bassig, 2019).

We also acknowledge that our assemblage of experts has concentrated on people with an HCI interest owing to the focus of the seminar's organizational body. This meant that other experts were not included, such as food scientists and chefs, who might have had interesting and valuable additions to the content of the seminar and could have therefore complemented our work. We suggest researchers interesting in taking this work further to also consider incorporating the views of such experts.

In addition, we acknowledge that our work could be complemented by future investigations that incorporate additional food-relevant perspectives and aspects that go beyond our focus on the food experience that is concerned with eating the food. For example, we have yet to investigate how technology could support the sourcing of food or how technology could facilitate the digestion of food. We encourage future work in this area and hope that our work could be useful in scaffolding such investigations.

Furthermore, we acknowledge that our article originated from a group of experts who mostly come from a privileged position, i.e., work in the developed world where food ingredients are widely available and culinary expertise in the form of hospitality experts such as high-end chefs is easily accessible. For example, our seminar participants worked with Michelin-starred chefs, contestants of national TV cooking shows and the "world's best bartender" award winners. As such, our results are biased and hence might give the impression that some of the outcomes that are possible if the challenges are resolved might only be within reach for those in similar privileged positions. This could be the case, however, it might just be a matter of time before innovations trickle through to more accessible food outlets. For example, we are pointing to the triumph of salted caramel that began as an expensive contemporary high-end restaurant ingredient but is now widely available and even served in fast food restaurants. We also point out that we see the identified challenges not necessarily as immediate problems that demand a quick fix, but rather as deserving closer investigations and research. Therefore, we believe that our challenges are only starting points that need to be developed and critiqued further by others, including academics and practitioners.

11. Conclusions

In this paper, we identified and described 10 grand challenges that the human-food interaction field is facing. Although current contributions already demonstrate the benefits the field can be making, we believe that finding solutions to these challenges will help HFI systems reach their full potential. We identified 4 groupings (technology, users, design and ethics) across the grand challenges. We note that our paper focused on the scientific challenges of HFI and only briefly touched upon considerations such as commercialization, biosecurity, world hunger, agriculture and social inclusion. Further work will be needed to better understand and tackle those issues.

We point out that the challenges we identified are both technically and conceptually complex, hence addressing them will require technical, epistemological, and social contributions from across a range of research communities. For example, challenges like those in the ethics grouping depend on knowledge from food science and represent a reframing of ongoing and important challenges in material HCI. Others, such as grand challenges from grouping "technology" are more technical in nature and call for contributions from adjacent communities such as sensory integration and hardware design. Furthermore, challenges related to the social aspects of eating (grouping "users") share links to work in social computing. As a result, addressing these challenges requires interdisciplinary collaboration. This does not only need to involve researchers from scientific disciplines, but also practitioners such as chefs, food designers, and restaurateurs who can bring domain expertise to the table as a way to confront broader concerns and turn them into solutions that affect the lives of everyone who eats, that is, all people. Such links will allow HFI to not only benefit from active research in these adjacent areas but also help contribute compelling use cases in kitchens, restaurants, and canteens that enrich all eating experiences.

Taken together, we hope that this article will bring the growing HFI community together, open new discussions, inform research goals, help researchers new to HFI, and provide a coherent view to outside stakeholders, such as industry corporations and funding agencies. HFI offers tremendous potential to enhance and enrich our food experiences. Addressing the challenges laid forth here will enable us to realize this potential and help introduce innovative advancements in this exciting field.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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