A Design Framework for Ingestible Play

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Ingestible sensors have become smaller and more powerful and allow us to envisage new human-computer interactions and bodily play experiences inside our bodies. Users can swallow ingestible sensors, which facilitate interior body sensing functions that provide data on which play experiences can be built. We call bodily play that uses ingestible sensors as play technologies "ingestible play", and we have adopted a research-through-design approach to investigate three prototypes. For each prototype, we conducted a field study to understand the player experiences. Based upon these results and practical design experiences, we have developed a design framework for ingestible play. We hope this work can guide future design of ingestible play; inspire the design of play technologies inside the human body to expand the current bodily play design space; and ultimately extend our understanding of how to design for the human body by considering the bodily experience of one's interior body.

CCS Concepts: • **Human-centered computing → Interaction design**.

Additional Key Words and Phrases: body-centric interaction, interior body, ingestible sensors, human-computer integration.

1 INTRODUCTION

Digital technologies are becoming more closely interwoven with the human body [85, 88, 89, 92]. Over time, people's interaction with computers has extended from stationary systems such as desktops to portable devices

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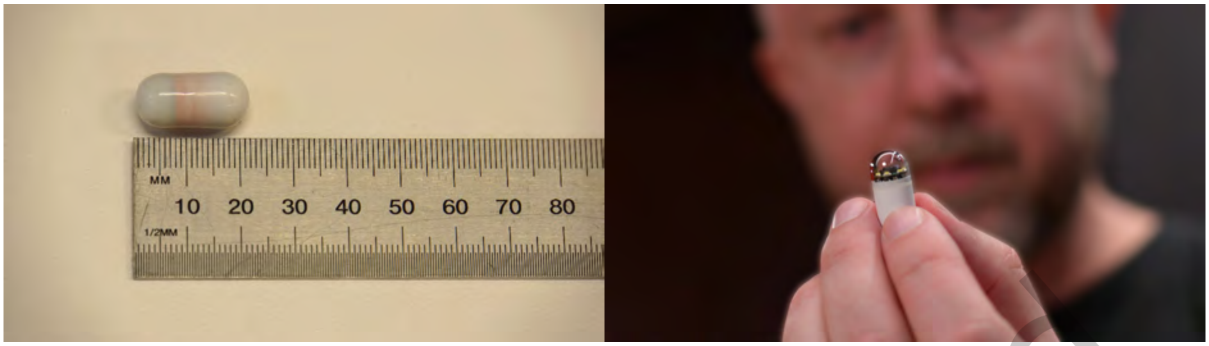


(a) An ingestible temperature sensor. (b) An imaging capsule.

Fig. 1. Ingestible sensors.

such as laptops, and more recently to devices such as mobile phones and smart wearables, that are always with the user; a trend towards human-computer integration (HInt) [28, 69, 92].

Prior work identified that the design space of bodily play largely depends on the affordances of play technologies [43, 81], hence the emergence of HInt technologies might provide novel opportunities for the design of bodily play. Contemporary commercial play technologies are either placed outside the human body, for example see Microsoft Kinect, Nintendo Switch, or on the body like a smartwatch. In this paper, inspired by the HInt trend, we consider a possible future for bodily play: one in which play technologies have physically entered the human body and accessed its interior parts.

We believe such a bodily play future can expand the current bodily play experience. Segura et al. [81] framed body games as "games in which the main source of enjoyment comes from bodily engagement". If current bodily play entertains players via bodily engagement, playing with technologies that enter the human body might entertain players via engaging them with their interior body. As a starting point of exploring this bodily play future, in this paper, we investigate how ingestible sensors, a digital sensor that can be swallowed, can be used as play technologies to facilitate intriguing bodily play experiences. We call bodily play that uses ingestible sensors as play technologies "ingestible play".

Ingestible sensors are self-contained electronic devices that can be swallowed by users. They are similar in shape to standard pharmaceutical capsules (Figure 1) and can perform specific functions inside the body [23]. Examples of ingestible sensors include temperature-sensing capsules (Figure 1a) [20], imaging capsules that incorporate small cameras (Figure 1b) that video-record the user's gastrointestinal tract (GIT)[1] [51], pH-monitoring capsules [41], medication-monitoring capsules [5], and gas-sensing capsules [54]. Most kinds of ingestible sensors do not contain a locomotion module and therefore move through the user's GIT and are naturally excreted within several days.

This work presents a design framework for ingestible play based upon our design and study of three playful systems around ingestible sensors. While all three systems have been reported in our prior publications [16, 67, 68, 71–76], these publications separately addressed each system that uses an ingestible sensor as a play technology. This work brings the three case studies together, and synthesizes our insights to generate a more systematic design framework for ingestible play. We hope that this design framework will support future research

[1]The gastrointestinal tract (GIT) is a series of hollow organs joined in a long, twisting tube from the mouth to the anus. The hollow organs that make up the GIT are the mouth, esophagus, stomach, small intestine, large intestine and anus.

by: guiding game designers to consider the novel design opportunities offered by bodily-integrated technologies; assisting game researchers to evaluate novel ingestible play experiences; and by inspiring interaction designers to consider the interior body when designing future intriguing bodily experiences. Ultimately, we hope this work can contribute to a future of digital play in which play technologies are closely interwoven with the player's body.

2 RELATED WORK

Our research builds on five areas of prior work: bodily play design; bodily play design in the HInt era; interactions focusing on the interior body; ingestible sensors in body arts; and biofeedback game design.

2.1 Bodily Play Design

Bodily play design has been extensively explored over the last decade [3, 29, 81, 86, 96]. Early work in bodily play design took a more third-person perspective: seeing the body as an object. For example, Segura et al. [81] suggested bodily play designers first identify what player activities (third-person perspective) the play technologies can sense as game input during the design process. Similarly, Rogers and Muller [105] presented a sensor-based play design framework that highlighted the need for designers to consider sensor properties and the couplings between player actions (third-person perspective) and system feedback. Following these prior works, we acknowledge the importance of understanding the affordances of play technologies in game design. Therefore, we as designers swallowed the ingestible sensors to understand the sensor affordances at the early stage of our design process.

Influenced by the third wave of HCI and the somatic turn in the field [78], an increasing number of researchers took a more first-person perspective on bodily play design. Segura et al. [80] proposed *embodied sketching*, suggesting designers understand first-person bodily experiences early in the design process. Mueller et al. [86] used the German words *Leib* (which means "lived body") and *Körper* (which means "physical body") to highlight that one should take both first- and third-person perspectives on the human body when designing bodily play. Mueller et al. [93] then expanded this understanding of differing perspectives, proposing *Erfahrung* as a third-person experience where one gains knowledge and *Erlebnis* as a first-person, tacit or "lived experience". Following these works, we develop our design framework for ingestible play to accommodate a players' first-person bodily experience.

While the above mentioned prior works aimed to provide a generalized design framework for bodily play, the advent of the HInt era means that we need to expand our current understanding of bodily play. Technologies that are more integrated with the human body can change how people experience their body, and they inspire novel design opportunities and challenges for the field of bodily play [91, 92, 100].

2.2 Bodily Play Design in the HInt Era

In recent bodily play research, we can see an increasing number of projects that take a HInt perspective on play experiences. For example, Byrne et al. [22] used galvanic vestibular stimulation (GVS) as a digital game design resource to create vertigo play experiences. Relatedly, Kunze et al. [62] proposed superhuman sports that use human augmentation technologies to surpass the human body's physical and cognitive restrictions and enable superhuman abilities. For example, Skeletonics[2] uses mechanical exoskeletons to facilitate an intriguing and entertaining superhuman sports experience. By wearing the system, users can experience themselves as a giant. Li et al. [70] presented an AI-powered interactive system, which utilized an arm-worm exoskeleton to actuate one's body for better game performance. However, the insights from these works had limitations. Byrne et al.'s work on vertigo games [22] limited their findings to vertigo experiences, which are hard for designers

[2] www.skeletonics-us.com/

to use to create other playful HInt experiences. Kunze et al.'s work on superhuman sports [62] took a practical perspective, primarily making an artefact contribution. Additionally, these works were based on only one case study. Consequently, there remains little systematic understanding of how bodily play can be designed in the era of HInt. Mueller et al.'s work on bodily-integrated play [88] was an initial attempt to offer such systematic guidance. However, while the authors proposed a set of design strategies to shed light on ingestible play design, they approached these strategies from a technical perspective. Specifically, they considered how bodily-integrated technologies can be used as design resources for digital play, and they did not articulate how bodily-integrated play might facilitate play experiences with a focus on the player's interior body. Responding to these gaps in design knowledge, our design framework aims to offer a systematic understanding of how ingestible play can be designed to engage people with their interior body.

2.3 Interactions that Focus on the Interior Body

We believe there is a need to explore the interaction design with a focus on the interior body. Prior cultural movements have shown people's eagerness to know, to interact, and even augment their interior body. Do It Yourself Biology (DIYBio) is a cultural movement that enables hobbyists to experiment with organic materials [63]. Within the DIYBio movement, the subgroup Body Hacking is relevant to our work. Body hacking usually uses technology to make functional and physiological modifications to the body [101], e.g., implanting a chip from a travel card into the hand. These cultural phenomena suggested that interactions that focus on the interior body can be culturally grounded.

In HCI, we can see works focusing on one's interior body. Some works used technology to externalize people's interior body. Fujisawa et al. [36] presented a virtual reality (VR) system "A Body Odyssey" that supported viewers watching food travelling through animated digestive organs and getting digested from a first-person view. Tactile and auditory sensations were designed to simulate the senses of touch and hearing. This work inspired us to add sensory stimulation to better engage players with their interior body and enrich the overall interactive experience when designing our second case study [76]. Boer et al. [15] presented "Loupe and Lightbox" that externalized the user's gut microbiome for closer examination, aesthetic appreciation and self-reflection. This work was in line with our work to support players' experience of bodily cultivation rather than mere self-tracking. Levisohn et al. [66] presented "Meatbook", an art installation that supported audiences interacting with an animated piece of flesh, aiming to provoke audiences' visceral responses. This work indicated the potential experience of interacting with the interior body. However, the experience of playing with one's own interior body is still unknown.

There are other works using the interior body as design material. Almeida et al. [2] presented "Labella" that supported intimate bodily knowledge and women's pelvic fitness by empowering them to look at their vagina in a humorous way. Similarly, Woytuk et al. [24] let people touch their bodily fluids, including menstrual blood, saliva, and cervical mucus to support explorations of their menstruating body. There are other works designing with intimate somatic data. Homewood et al. [48] presented a home-based device for ovulation tracking to better support conception. Helms [46] explored the potential of utilizing intimate and somatic data to manage one's urination. These works showed how knowing, interacting with and experiencing the interior body can better support bodily engagement, while the experience of having technology "invading" our interior body remains largely unknown. However, we found that arts projects can provide insights, hence we turn to these next.

2.4 Ingestible Sensors in Body Arts

Artists have already used ingestible sensors to express their understanding of the human body. For example, the artist Stelarc inserted an ingestible sensor containing a beeping device and a flashing light into his body to express his understanding of the human body [115]. He argued that the body is "hollow" and useable as a public exhibition space. Poope [52] designed "Audiopill", allowing users to experience music from their insides after swallowing an ingestible sensor. The pill vibrates musical beats inside the user's GIT for approximately ten hours. Warnell [120] swallowed an imaging capsule (an ingestible sensor containing a camera) and showed audiences the captured video of his GIT to highlight the use of internal body images beyond their medical applications. Other artworks do not use ingestible sensors but still involve the interior body data. For example, Mona Hatoum exhibited "Deep Throat", an art installation that projected the GIT's inner appearance on a plate placed on a fine dining table [60]. Another of Hatoum's works, "Corps étranger", used an endoscope to film the artist's exterior and interior body in turn and then projected the film onto the floor of a cylindrical structure that viewers entered. Hatoum's works aimed to show audiences the unknown human body parts and facilitate reflections upon the "violent appropriation of contemporary imaging technologies" [112]. These artworks indicated how ingestible sensors might influence one's bodily experience and highlighted the potential for using ingestible sensors as a material for designing bodily play.

2.5 Biofeedback Game Design

Biofeedback games incorporate players' biometric information [30] into play experiences. Most biofeedback games use players' bodily data to understand their emotional or physiological states and either adjust gameplay for increasing game immersion [30, 97] or change the game difficulty to keep the player in a state of "flow" [25, 118]. These works in biofeedback games may involve the player's interior body but they do not put it at the center of the experience.

Unlike exterior body parts such as limbs, humans usually experience low agency over their interior body since most of our internal organs operate independently of our conscious control [64]. Given the importance of agency in facilitating positive play experiences [118], this low agency makes it challenging to design engaging interior bodily play experiences. With respect to biofeedback game design, Nacke et al. [97] suggested that where we can directly control biodata, such as eye movement and muscle flexion, the design should use it to drive quick and visible in-game responses. Biodata that can only be controlled indirectly, such as galvanic skin response and heart rate, should be designed to influence features that alter the game world, such as in-game weather. Building on these works, our design of interior bodily play has considered players' low agency over their interior body. For example, when developing the case study systems, we employed ambiguity [39] around the system's feedback as a strategy to dampen any frustration caused by low agency.

2.6 Summary

This review highlights the HCI field's limited understanding of ingestible play. The field has rarely explored ingestible sensors as interactive technology. Current design theories on bodily play are not adequate for ingestible play design since they were primarily generated based on projects focusing on the exterior body. In summary, ingestible play design remains an under-explored topic. As technologies are becoming closer to the human body, it becomes more necessary to explore the opportunities provided by ingestible sensors as play technology and how to design for them.

3 METHODS

In this section, we elaborate on the research methods used to understand the design of ingestible play.

3.1 Concept-driven Design Research

Concept-driven design research is a method for generating new design knowledge by creating novel design artifacts [116]. According to Stolterman and Wiberg [116], concept-driven design "illustrates how cutting-edge technology can be used as a design material in the realization of new ideas". Such a design may not reveal new technology that is wished by any user. Ingestible play represents a novel design space in the field, and few

Fig. 2. A vision of experiencing the body as play (image from [86]).

works have investigated ingestible sensors as a design material for bodily play. We believe that rather than, for example, aiming to satisfy specific user needs, conducting concept-driven design research is more appropriate to understand the design of ingestible play.

Concept-driven design research does not present an arbitrary belief about the future. Instead, it should be grounded conceptually and historically [116]. Our belief that ingestible play is an emerging area worth exploring is based on how playful interaction has changed. Figure 2 shows how Mueller et al. [86] summarized the evolution of bodily play with digital technologies and envisioned a future of digital bodily play: people progressed from playing digital games in front of computers in a seated position to playing digital games utilizing sensing technologies capable of engaging their whole body. Based on these developments, Mueller et al. [86, 88] envisioned that in the future, the digital content might integrate with the human body so that players can experience their body as digital play. As such, players no longer experience their body merely as “game controllers”, but as an integral part of the “digital play” experience. This vision provided the conceptual and historical ground for the design of ingestible play.

3.2 Research Through Design

In this work, we use research through design (RtD) to generate design knowledge of ingestible play. RtD is a common approach for developing a theoretical contribution via concept-driven design [123].

The emergence of RtD can be traced back to 1994 when Frayling [35] raised a concern regarding the dichotomy between art/design and research. Frayling argued that there is 1) research into art and design that focuses on theoretical perspectives, including historical research, aesthetic and perceptual research, etc; 2) research through art and design that includes materials research (e.g., augmenting materials for jewelry design), development work (e.g., designing novel technologies for intriguing uses), and action research (e.g., documenting the design practices); and 3) research for art and design that highlights the efforts for preparing for design practices such as gathering materials. With research for art and design, the research outcome is the designed artefact that embodies designers’ thinking. According to Frayling [35], our work can be seen as a development work and hence is “research through art and design”. Current uses of ingestible sensors are either for medical purposes or for artistic expression. In contrast, we are using the sensor to explore future play experiences where play technologies are integrated with the human body.

Frayling's work provided a basis for later RtD research in HCI [8, 38, 123, 124]. Gaver [38] discussed critical issues in RtD research, arguing that different from science disciplines, we should moderate expectations of generating extensible, verifiable, and convergent design knowledge. Inspired by this, we aim to present key design implications of ingestible play, rather than giving prescriptive design suggestions. Bardzell et al. [8] argued that most RtD research focused on the designers' intentions and annotations of artefacts, while the critical perception is also important in generating design knowledge. This inspired us that rather than simply reflecting on our design process, we also need to evaluate our prototypes in the real-world setting with real users to understand how others understand and engage with our design.

The above works all influenced our design knowledge generation to some extent. Meanwhile, our work mainly followed the understanding of RtD presented by Zimmerman et al. [123, 124] in practices. Zimmerman et al. [123, 124] used design as a way of inquiry and presented a practical model to guide the RtD process. This approach enables designers to reflect on their design through prototyping, leading to the evaluation and examination of the design process, invention, relevance, and extensibility of their design [123].

Following [123, 124], we built three ingestible play prototypes as case studies [71, 75, 76]. We evaluated each prototype in real-world settings through field studies and gathered qualitative data of user experiences through semi-structured interviews. The interview data were analyzed via thematic analysis, leading to a set of findings. We then reflected on the hands-on design experience of creating the three prototypes and our study results, and finally articulated a design framework for ingestible play.

3.3 Field Study

For each case study, we conducted a field study to understand the player experience in a real-world setting. Koskinen et al. [61] presented that design research can be conducted in the lab, field or showrooms. A lab study provides a controllable environment and therefore enables researchers to focus on one variable at a time. Studies in a showroom are usually set up for radical designs in exhibitions and galleries to provoke critical reflections. A field study investigates the system in a real-world situation with real users, enabling researchers to evaluate the design in the context of use [61]. A field study, therefore, helps researchers to generalize the findings to the real world rather than a study environment.

In our work, we conducted field studies to understand the user experience of ingestible play in an everyday context. Doing field studies can provide a richer understanding of how users interact with the technology and how users adopt, use, or abandon the technology in a real-world context [56, 57]. Moreover, as the ingestible sensors used in this work usually stayed in a user's body for 24–36 hours, conducting field studies over several days allowed for the full use of the system and enabled a more comprehensive understanding of ingestible play. Therefore we have decided to conduct field studies to understand the player experience in all case studies.

To recruit participants for our field studies, we followed a hybrid of the convenience sampling and semi-controlled recruitment methods [111]. We began recruiting participants within our personal and the lab's social networks (e.g., Google groups), and also put recruitment posters on the campus. Moreover, we adopted the snowballing method [18], asking participants whether they could recommend this study to other potential participants. No compensation was provided in all case studies.

3.4 Data Collection and Analysis

In all case studies, we used semi-structured interviews to collect participants' responses to the prototypes they have experienced. We followed a set of questions asking the participants' expectations, motivations, feedback on the system, play experiences, and use contexts to guide the interviews, while also following up with participants on the interesting topics that emerged during the conversation [13]. We chose to conduct semi-structured interviews as we hoped to leave sufficient room for topics to emerge, supporting a deeper elucidation of participants' responses and thinking processes [109].

We used inductive thematic analysis to analyze the interview data [17]. For each study, the qualitative data was analyzed by two of the researchers. One researcher first transcribed the interview data from the audio-recording and shared the transcript with the other. Next, the two researchers became familiar with the transcripts by reading them three times, then coded the data independently. Following inductive thematic analysis, our researchers independently identified a set of potential codes in the data corpus guided by the question "how can we design ingestible play to engage players with their interior body?" Then the two researchers gathered and discussed the potential codes and developed a final set of codes. After deriving a set of codes, the two researchers iteratively clustered them into higher-level groupings. This thematic analysis followed the same practice in similar qualitative HCI research [4, 58].

In the next sections, we will introduce our three case studies.

4 CASE STUDY

In this section, we will present our three case studies of ingestible play.

4.1 Case Study 1: The Guts Game

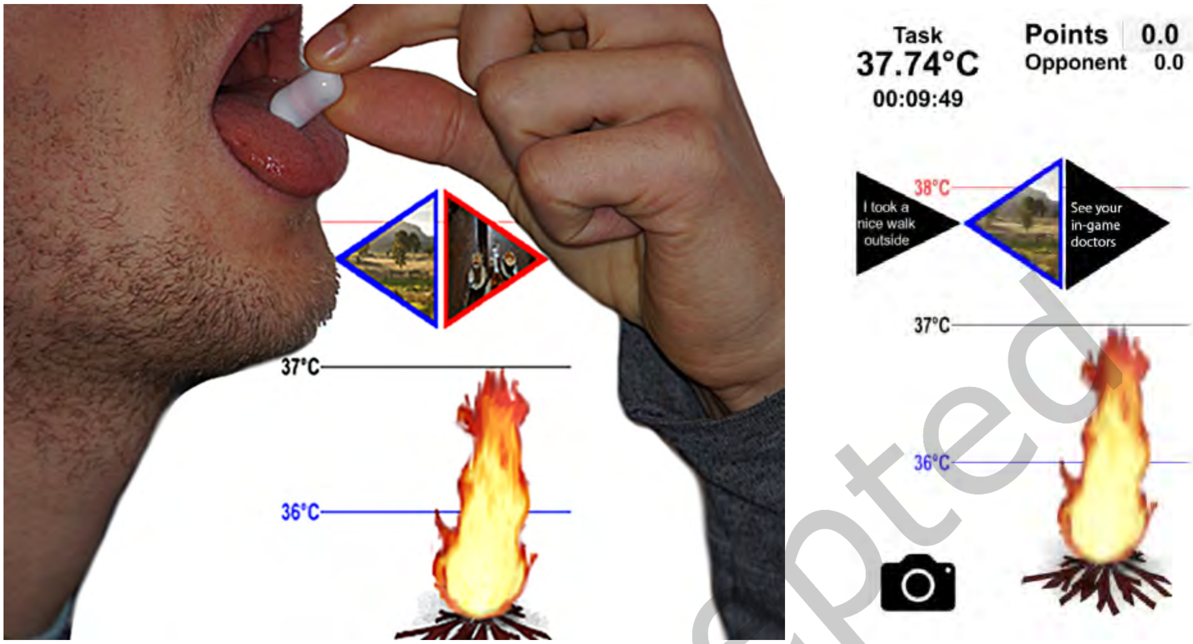
The Guts Game [71] is a two-player mobile game with a single-use ingestible temperature sensor as play technology (Figure 3a). To start the game, the player swallows the sensor that measures temperature every ten seconds and wears a data recorder on the waist to receive the temperature data. The recorder then forwards the data to a smartphone used for play (Figure 4).

With the Guts Game, the game app visualizes the player's interior body temperature through the image of an animated fire (Figure 3b). We hoped this visualization could help players build a conceptual link between temperature and flame easily. The Guts Game requests players to regulate their temperature to complete game tasks and gain game points. Players can exercise, eat, drink, etc. to change their body temperature, and the game does not provide any guidance or set any restrictions on the activities that the players can perform. During the game, the players can send pictures and Twitter-length messages to each other. The game ends and the winner (the one with the most points) is declared when one of the players excretes the sensor.

The Guts Game has three task modes: general mode, feeling mode and challenge mode. The general mode requires players to change their temperature to reach the task's goal. In the feeling mode, the height of the visualized fire remains stable so players need to estimate their body temperature. Once the players feel that they have reached the goal, they can submit the task. The closer a player's temperature is to the goal, the more points they are awarded. In the challenge mode, players can set a temperature goal. After reaching this goal, the player can send the same challenge to the co-player. After receiving a challenge task, the co-player cannot be assigned any more task and need to complete the challenge to unlock the gameplay. If the co-player cannot tackle the challenge, the gameplay will be automatically unlocked 1.5 hours after receiving the task.

4.1.1 First-person Experience Design.

As our first case study, we had limited knowledge on the user experience of ingestible sensors when designing the Guts Game. To understand the first-person experience of having a digital sensor entering the body, we conducted a pre-design study where two researchers swallowed an ingestible temperature sensor together. After ingesting the sensor, the two researchers performed a series of activities such as drinking water of different temperatures, eating ice-cream, relaxing, and physically exercising with various intensities until they excreted the sensor. During the study, they took notes of their activity, their temperature changes, and also their experience.



(a) (b)

Fig. 3. (a) With the Guts Game, the player swallows an ingestible temperature sensor to play the game. (b) A screenshot of the Guts Game after receiving a general mode task. The task's goal is displayed on the upper left. The height of the flame represents the player's body temperature. The messages and pictures sent by both players are displayed in the triangles above the flame.

We found that there were delays between the activities and temperature changes. The delayed time were influenced by the sensor's location. When the sensor was in the stomach, the temperature usually changed 20–40 seconds after drinking or eating. When the sensor entered the intestines, drinking water might only affect the temperature data if the stomach was empty and there might be a delay of 3–5 minutes to see the change. Additionally, the intensity of exercises also affected the delayed time. For example, in our pre-study, the body temperature began to rise 8 minutes after starting to walk at normal speed, but only one minute after starting intense exercise. We believe these features could provide great opportunities for players to learn about their interior body through play, e.g., letting them become aware of their GIT structure, and teaching them how their activities can affect their body. Therefore, in the design of our prototypes, we gave players space to freely choose their activities. Moreover, in our pre-design study, the two researchers gained more courage when swallowing the sensor together, and they were eager to share their experience and findings with each other. Therefore, we supported social interactions in all the case studies.

4.1.2 User Study.

To understand the Guts Game's design and user experience, we conducted a field study with 7 pairs of players (14 participants). None of them were HCI researchers. Two of them were from the game industry. During the study, we added a game narrative to make the game more appealing. We served the two players nice food and then dressed up like doctors, telling them they were infected by a special parasite hidden in the food. The parasite

Fig. 4. The equipment we gave to players. The waist bag was used to contain the data recorder so that players could wear the recorder around their waist. The waterproof bag was for players to put the smartphone into when showering or swimming.

was sensitive to the surrounding temperature so it could be weakened by adjusting the body temperature. We have developed the Guts Game to support players adjusting their temperature to wipe out the parasite. After the narrative, the players swallowed the ingestible sensors and received the devices they need for the game. Then they left our lab and went back to their daily routine. After the game ended, they came back to our lab for an interview.

This study led to 12 findings based on the interview data analysis. We found that players enjoyed the game and regarded it as novel and intriguing, particularly because the play technologies physically entered their body. Players believed that this suggested a future for bodily play and they felt excited to be involved in the "next big thing". Moreover, players thought that the ingestible sensors let them experience their body as the game interface, unlike other devices, such as smartphones and wearables, where users experienced the technology as the game interface. Players also reported that they enjoyed the ubiquity of ingestible sensors (always inside the body) in comparison with the "less ubiquitous" play experience of smartphones. In response to this study, we decided to remove smartphone in our next prototype and designed the whole system to be wearable. Moreover, to ensure the system to be more ubiquitous, we decided to use always-available game feedback so that players can experience their body at any time and place.

4.2 Case Study 2: HeatCraft

HeatCraft [76] is a wearable system for players to playfully experience their interior body temperature measured by an ingestible sensor via on-body thermal stimuli (Figure 5). Each player wears a waist belt that attaches a data recorder, a semi-transparent bag, and two overlapping heating pads. The semi-transparent bag includes an Arduino and an associated battery, and a power bank to power the heating pads (Figure 6). The data recorder receives temperature data from the ingestible sensor and then transmits it to the Arduino wirelessly. The Arduino

Fig. 5. The two players wore the HeatCraft system and ran in a park.

then converts the data to the thermal stimuli's target temperature according to our designed mapping and adjusts the heating pads' temperature to the target temperature.

4.2.1 First-person Experience Design.

In this work, we mainly adopted a first-person experience design approach for designing the system's feedback. In addition to heat, we also considered other embodied modalities as feedback. In our study, we found that an always-available haptic experience might disturb players' daily lives. Also, olfactory feedback could be hard to notice and one might feel difficult distinguishing the changes in the smell intensity. Moreover, in certain contexts, people might not want the smell as others can also smell it. For thermal feedback, all the three researchers involved in this first-person experience design process appreciated the feedback as being always-available, comfortable, unobtrusive, easy-to-perceive and private.

After deciding to use thermal feedback, we conducted another first-person study to design the mapping between the player's body temperature and the thermal stimuli temperature. Two researchers experienced heat via heating pads with different intensities. Researcher A adjusted the temperature of the heating pad which was outside of Researcher B's T-shirt and asked researcher B to report their real-time body experience. Then the two researchers swapped their roles. This process was repeated five times. Results showed that the lowest heating pad temperature that can be perceived was $28°C$ on average and there was an unpleasant sensation after the temperature reached $50°C$. Therefore, we designed the temperature of the heating pad to be between $28°C$ and $50°C$.

4.2.2 User Study.

We invited 16 participants (8 pairs) to experience HeatCraft in the field. Two were HCI researchers and two were computer science students with an interest in HCI. During the study, we did not restrict players' activities so they could freely explore the ways to affect their body. In keeping with our appreciation of social interactions, we encouraged each pair to spend at least three hours physically together during the study to ensure there was enough time for social interactions to take place.

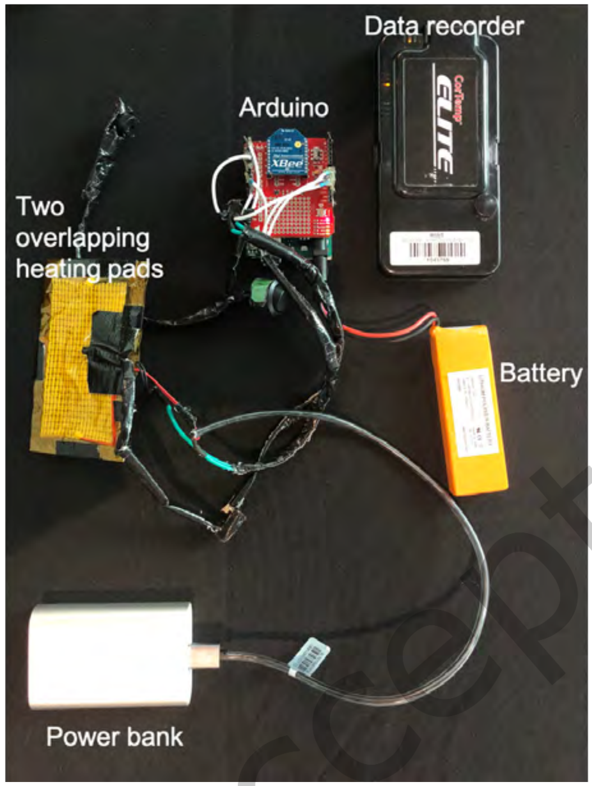


Fig. 6. The HeatCraft system.

The study resulted in 18 findings. With respect to ubiquitous playful experiences, HeatCraft improved upon the Guts Game primarily because we designed the HeatCraft system to be wearable and adopted always-there thermal feedback. Indeed, players reported that they experienced a certain level of integration with the HeatCraft system. Moreover, our results showed that HeatCraft increased players' awareness of their body, daily activities and surrounding environment. HeatCraft helped us move towards a more complete understanding of ingestible play. However, we believe that this understanding was still not enough to develop a design framework. The Guts Game and HeatCraft use ingestible sensors which measure the player's interior body using one-dimensional data. Our next case study explored multidimensional data: the player's real-time GIT video.

4.3 Case Study 3: InsideOut

InsideOut [75] is a playful wearable system that allows players to interact with their GIT video. InsideOut is based on a commercialized capsule endoscopy system (Figure 7a), comprising an imaging capsule [3] (i.e., an ingestible sensor that incorporates a tiny camera), a waist belt containing an antenna array for receiving wireless signals from the capsule, a recorder receiving data from the antenna array, and software to support real-time viewing of the video when the data recorder is connected to a computer. During usage, the data recorder is held in a pouch and worn by the user. In addition to the endoscopy system, InsideOut comprises a display (iPad), a

[3]OMOM SmartCapsule Endoscopy System. http://english.jinshangroup.com/capsuleendoscopy.html

(a) (b)

Fig. 7. (a) A player with the InsideOut system is moving the body to see whether the GIT's shape can be influenced. (b) The system diagram of InsideOut.

laptop (MacBook) and a power bank to power the laptop (Figure 7b). The InsideOut player carries the laptop in a backpack. The laptop streams the video collected by the endoscopy system to the TouchDesigner [4] for composing and interactivity. The player wears the iPad in front of the body. The transformation of the video is based on the player's body movements and environment, which are sensed by the iPad and sent to TouchDesigner via GyrOSC[5]. The output video from the TouchDesigner is shown on the iPad via Duet Display[6]. Players can influence their GIT by exploring a variety of actions, such as eating, drinking and moving. In addition, we designed six play modes to enrich the play experiences. For example, a play mode called "body balance" maps the video to the surface of a rolling ball placed on a springboard. Users need to move their body to balance the springboard to keep the ball from falling down.

4.3.1 *First-person Experience Design.*

In this work, we have used first-person experience design to iterate the prototype design [19]. Here we take how we designed the system's wearability as an example. HeatCraft showed that supporting always-available interactions can contribute to ubiquitous play experiences. Hence, we designed InsideOut integrated with a T-shirt with a display in front of the body to support always-available play. The player can lower the head to view the screen at any time. The results of the prior studies also showed that players enjoyed speculating on the sensor's location. Inspired by this, we designed the display to move from the player's chest to the abdomen as play progresses. We thought the move of the display can be seen as a literal metaphor of the capsule moving from the oral cavity to the large intestine. We tried this on ourselves and found that this might cause confusion when the display's location was inconsistent with the video information, e.g., when the video was showing the stomach wall while the display was in front of the small intestine. We also invited our lab members and friends to experience this prototype without telling them the idea behind the design. Most of them found the moving display to be confusing as they did not connect the moving display to the moving capsules. Therefore, we decided to no further support this design feature.

4.3.2 *User Study.*

[4]TouchDesigner is a software that supports node-based visual programming for real-time interactive multimedia content. www.derivative.ca/
[5]GyrOSC is an application that sends the data sensed by sensors embedded in an iPhone, iPod Touch or iPad to any OSC-capable host application over a local wireless network. www.bitshapesoftware.com/instruments/gyrosc/
[6]Duet Display is an app that supports users to turn an iPad into a second monitor. www.duetdisplay.com/

We invited seven participants to experience InsideOut in the field. Two of them were HCI researchers. Participants were invited to our lab to put on the system and then went back to their daily routine. After around eight hours (the same as the battery life of the imaging sensor), the participants went back to our lab for a semi-structured interview. The study led to 11 findings. The results showed that players appreciated the experience of seeing and playing with their interior body video with InsideOut. Although they might, at first, have felt that seeing their GIT was "confronting," they enjoyed getting to know the invisible parts of their body through the play. The design and study of InsideOut helped us understand the design of ingestible play with ingestible sensors that sense multidimensional data and step towards a fuller understanding of designing ingestible play.

5 ETHICS CONSIDERATIONS

Ingestible play raises ethical questions due to its invasive nature. Although providing a full discussion is beyond a single article, we believe it is important to start a conversation about ethical issues as ingestibles are becoming more common.

We acknowledge that there are people regarding the use of invasive technologies for non-life-critical purposes such as play as questionable. However, we argue that besides risks, ingestible play might afford entertainment, education, health benefits, etc. In all our case studies, participants were made aware of the potential risks of ingestible play, yet were still willing to participate in the study, even without compensation. This might suggest that there are people who might regard ingestible play as worthy of engaging in, despite its potential risks.

Nevertheless, we stress that designers need to be mindful of the ethical issues. According to Benford et al. [12], designers should concern themselves with informed consent, the right to withdraw, privacy and anonymity, and managing risk when designing uncomfortable interactions. Here we discuss the ethics of ingestible play from three perspectives: informed consent, privacy and anonymity, and managing risk. We do not include the right to withdraw, as we see informed consent as an ongoing process where the right to withdraw is part of the consent [117].

5.1 Informed Consent

Strengers et al. [117] adopted the FRIES model [102] that includes five themes (i.e., freely given, reversible, informed, enthusiastic, and specific) to discuss the design of consent in HCI. Here we use this as a basis to discuss informed consent in ingestible play.

Freely given means consent is a choice one makes without pressure, manipulation or under the influence of drugs or alcohol. In ingestible play, one might feel excited about the novel play opportunity without fully considering the risks. In our work, participants were given an information sheet introducing the technology they would use, potential activities they might do and potential risks. We also gave people a cooling-off period (at least 24 hours) before starting the study.

Reversible means anyone can change their mind at any time. However, ingestible sensors can only be removed by surgery after being swallowed. In our work, players were informed that they could withdraw from the study at any time. Although the sensor might hard to be removed, the other parts of the system could be removed at any time.

Informed means one can only consent to something if they have the full story. However, in ingestible play, it could be hard to predict the extent of players' mental discomfort before actually starting the game. In our work, participants were informed that they could contact the research team if they felt any discomfort relating to the study and the researchers would try to help. The design of ingestible play can also create different levels of experiences so players can adjust the level of potential discomfort. For example, players could choose from play modes with different levels of difficulty with the Guts Game: easy, medium and hard. InsideOut provided players with different play modes with different levels of abstraction of the GIT video.

Enthusiastic means one should only do what one wants to do. This perspective is usually not a big problem for ingestible play, as play is voluntary in nature [50].

Specific means saying yes to one thing does not mean saying yes to other things. This theme might bring challenges in ingestible play. For example, our studies were conducted in the field without researchers being on-site, hence it was challenging for designers to intervene when players interacted with the system in an unexpected way that they had not consent for. In our study, we have listed all the potential activities they could do during the study and emphasized all the things they could not to do. We also gave participants all the researchers' contact numbers so they could ask us whether something was fine to do at any time. There was only one participant, of the Guts Game, who contacted us, asking whether it was safe to drink hot tea.

5.2 Privacy and Anonymity

The privacy and anonymity issue should also be considered in ingestible play. Interior body data can be regarded as a private medical record. With ingestible play or any other non-medical purposes of ingestible sensor-based interactions, ethical questions might arise, such as, who should have the right to access the user's interior body information? Who owns the data? In some cases, ingestible play might be designed as social games. If so, should the co-players have access to other players' data? Should the game support the player sharing the data on social media? Etc. In our studies, we requested permission from players before using their anonymous data in our publications. Designers should notice that our studies only involved a small number of participants. As interior body data becomes more pervasive in the future, data privacy risks require further consideration.

5.3 Risk management

In ingestible play, designers should manage health and safety issues. In our study, no player expressed safety concerns during and after the game. We asked our participants whether they felt unsafe before the study and they expressed that they believed the sensor should be safe as it was a commercial product that was cleared by the authorities (as indicated in our information sheet). Moreover, they said that our briefing made them understand the potential risks and how to deal with these risks. Hence, they did not feel anxious regarding any safety issues. Nevertheless, it is important for designers to be clearly aware of the health risks of integrating digital technologies with the human body. In this section, we provide a brief summary of the major risk factors of ingestible play we have considered during the study.

5.3.1 Risk of Retention.

With ingestible sensors, the primary risk is the sensor's retention in the GIT. This risk is low, as ingestible sensors have been widely recognized as safe for healthy people to use if smaller than 11 mm in diameter and 28 mm in length [55]. In our studies, we established a screening protocol that required players to complete a questionnaire about their health conditions. With InsideOut, we also invited a health professional to further evaluate each player's suitability for the study, as the imaging capsule has rarely been used outside the medical domain. We also encouraged potential participants to talk to their doctors before participation and highlighted that they should go to the nearest hospital if there would be an emergency occurring during the study, although we did not anticipate that this will be the case. In our study, there was no emergency issue.

With the Guts Game and HeatCraft, participants could get to know whether the sensor had been excreted based on the patterns of the received data. However, with InsideOut, the sensor's battery might have run out before the sensor excretion, and therefore it might be hard for participants to determine whether the sensor has been excreted. We learned that with endoscopy procedures in hospitals, doctors usually tell patients to come back to the hospital if they feel uncomfortable or experienced any pain. We established a similar process, telling participants to go to the nearest hospital and also contact us if they felt uncomfortable or experienced any pain after the study. Moreover, we envisioned that, in some cases, participants might be concerned that the capsule did not pass. We suggested participants contact us in this case. The health professional in our team would look at the images captured by the capsule that might indicate the capsule's passage. If the capsule was not observed to be passed to the colon, an abdominal X-ray could have been obtained after 3 days to confirm its passage, and we told the participants that we would have paid for this cost. In our case studies, none of the participants experienced any discomfort or asked for an X-ray procedure.

5.3.2 *Risk of Conducting Inappropriate Activities.*

Once a player was deemed eligible to participate, we provided them with preparatory instructions, including information on what they should and should not do based on the product manual's directions and our health professionals' advice. For example, players were warned not to go near functional magnetic resonance imaging (fMRI) machines while the sensor was inside their body. We also provided players with all the researchers' contact numbers, guidance for first aid, and the study do's and don't's. During the study, researchers were contactable via mobile phone to clarify any queries. None of the participant contacted us regarding any health issues. However, there were inquiries regarding technical issues. With the Guts Game, the system transmitted the data from a data recorder to the mobile phone, where the connection sometimes broke, and players needed help with reconnecting the devices. We had printed a trouble-shooting instruction sheet for players, however, some still had difficulties around solving technical problems and therefore contacted the research team to seek help. All the technical issues were solved during our study.

5.3.3 *Risk of Injuries.*

There is a low risk that the participant accidentally might got injured during the study and needed to go to hospital when the sensor is inside their body. During our study, participants were provided with a document describing the project and the ingestible sensor we used so that any doctor can get all the details immediately if there is ever a need. In addition, we highlighted that if this would happen, participants could forward the contact numbers of the researchers so that doctors could call the research team if there is an emergency. During our three case studies, this did not happen.

5.3.4 *Risk of Exhaustion to Achieve Game Goals.*

There is a risk that participants could overwhelm themselves to change their interior body, e.g., raise their body temperature beyond safe levels during the play. In our studies, we highlighted that participants should conduct all activities within safe limits and only for as long as they felt comfortable and should not overexert themselves. Moreover, we set game goals that we believed were achievable (if there were game tasks) based on our first-person design approach. For example, in the Guts Game, we only required players to achieve small temperature changes. In our case studies, none of the participant reported any exhaustion during the study.

5.3.5 *Risk of Identifying Something Perceived as Abnormal.*

There is a risk that participants could find that their bodily data collected by the ingestible sensor was something that could be perceived as abnormal. We highlighted that this study was not a medical diagnosis as we did not strictly follow the rules of a medical procedure. Therefore, participants should not use the data collected in the study as health indicator. We acknowledge that there is a small chance that participants might still feel mentally stressed. We told the participants that if they become upset or stressed as a result of their participation in the research project, members of the research team would be able to discuss what support is available. In our case studies, none of the participant expressed any concern regarding identifying something in the data that could be perceived as abnormal.

5.3.6 *Risk of Causing Offence to Others.*

In some cases, there might be risks associated with social interactions, e.g., when sharing the interior body data or talking about the study to others. We informed players that they could share any aspect of this research with spectators, including motivation, technology, design and experience. If players found spectators' questions too hard or uncomfortable to answer, they could provide the researchers' contact phone numbers. Moreover, players could stop the study at any time when they felt uncomfortable. With InsideOut, we considered the risk that a public video display of the interior body could offend bystanders. We suggested players show the video only at home and in the workplace. The system also features a button to hide the video. Additionally, players were required to inform potential spectators such as housemates and workmates about the study before the player became involved. We instructed players to continue with the study only when potential spectators felt comfortable.

5.3.7 *Ethics of First-Person Design.*

We would also like to highlight that designers should consider ethical issues when they try the ingestible sensor by themselves. In the case study of the Guts Game, we applied for approval from the ethics board of our organization before conducting the first-person design where we as researchers swallowed an ingestible temperature sensor ourselves. The two researchers who swallowed the sensor confirmed that their health condition met the sensor-using requirements under the supervision of their doctors.

6 THE DESIGN FRAMEWORK OF INGESTIBLE PLAY

By synthesizing the results of the case studies and the reflections of our hands-on design practice, we generated a design framework of ingestible play.

Our research question is "how can we design ingestible play to engage players with their interior body?". Consequently, the design framework should reveal how ingestible sensors can be used to facilitate engaging bodily play experiences with a focus on the interior body. To understand the player's bodily experience, we turned to the four bodily experience dimensions of Grīnfelde's phenomenological work: the material dimension, the functional dimension, the affective dimension and the social dimension [42] as the basis of our framework. We based our framework on Grīnfelde's theory as it provides a, what we believe suitable, vehicle to analyze the player's bodily experience and hence engagement in ingestible play. With our work, we hope to better understand how ingestible play could be designed to facilitate engaging bodily experiences. As a result, we need to gain a better understanding of our bodily experiences and analyze how the bodily experience can be augmented via design based on our case studies. We believe that Grīnfelde's theory could be seen as a good tool to understand one's bodily experience as it provides us with four lenses to analyze interactive systems that augment one's bodily experiences. Such an approach of analyzing experience from different lenses have been used in other HCI works. For example, Mueller et al. [87] presented a framework for exertion interactions that is structured using four lenses. Each lens was inspired by van Manen's phenomenological work that analyzed one's lived experience. Similar to Mueller's work, we refer to Grīnfelde's phenomenological work to understand the player's bodily experiences via four dimensions. Based on Grīnfelde's work, all the authors of this article reflected on the study results and their design experiences of ingestible play and discussed how our design leveraged ingestible sensors to facilitate player engagement with these four dimensions of interior bodily experiences. In the next sections, we will elaborate on the design framework. For each dimension, we will first briefly elaborate on the original meaning presented by Grīnfelde [42] and then present how ingestible play can be designed to augment the interior body experiences from the perspective of this dimension.

6.1 The Material Interior Body

The human body can be conceived of as a material object [42]. However, this material dimension rarely manifests in our everyday experiences [42, 64]. We usually perceive the material dimension when experiencing the disruption of bodily functions or in extreme situations. Slatman [114] used an example from the novel *Slow*

Man in which a man calls his amputated legs “the ham”, indicating that he experiences his legs as a purely material thing, an object other than part of himself.

We can barely engage with the interior body’s material dimension because of the interior body’s invisibility and inaccessibility. Without imaging technology or surgery, we cannot see or touch our interior body. However, with ingestible sensors entering our body and providing interior body information, ingestible play has the potential to enrich the player’s experience with the material dimension of their interior body.

6.1.1 Design with Body Boundary to Highlight Material Body.

Usually, we consider skin as the boundary of our material body. Ingestible sensors physically enter our body during the play and hence cross one’s body boundary. All our case studies demonstrated that this body boundary crossing could be playful. A finding from the Guts Game study was "the integration between the sensor and body facilitated the players’ emotional response", which highlighted that players experienced some sort of thrill to swallow a foreign object. HeatCraft and InsideOut players reported similar experiences.

Such a playful thrill experience can even be prolonged via design choices. For example, with InsideOut, we designed the video shown in front of the player’s body to let players feel that their body became transparent, and the interior parts of the body were publicly accessible, which further “eliminated” the body boundary. Such a design highlights the fact that the sensor crossed the player’s body boundaries when being swallowed. All the InsideOut players regarded such experience as playful.

However, an intense thrill is not always a good thing. In the Guts Game, we designed a game narrative to guide players in ingesting the sensor. Participants reported that the narrative made the ingestion more fun and meaningful, and helped them relax when they felt a bit nervous to swallow the sensor. Moreover, with Guts Game and HeatCraft, players reported that swallowing the sensor with a co-player made them less nervous as they felt they were having an adventure together. With InsideOut, players did not have someone ingesting the sensor together. However, we observed that most players held the sensor in a way to capture the surrounding environment and their oral cavity via the capsule, and looked at the resulting video shown on their body. Such an engagement with the sensor appeared to help them relax and get to know the sensor better according to their report. Taken together, in all our three cases, the thrill experience of swallowing the sensor appeared to be dampened when the ingestion was designed to be playful.

The thrill experience can also be dampened by increasing player acceptance of ingestible sensors. Technology acceptance refers to one’s willingness to use particular information technology for the tasks it is designed to support [32]. Prior works have identified various factors that influence user acceptance of information technology [65, 84, 121]. Our three case studies confirmed some factors presented in the Technology Acceptance Model (TAM) [65]. For example, the TAM suggests that computer playfulness can increase user acceptance, which aligns with the playfulness designed into our ingestible experiences. Similarly, end-user support can increase user acceptance [65], which is akin to providing players with the system’s instructions and the researchers’ contact details for any technical issues, as we did in our three case studies.

In addition to this thrill experience of swallowing the sensor, we should not forget that an ingestible sensor does not only cross the body boundary once. Different from other invasive technologies like implantables that stay fixed inside the human body, ingestible sensors move along the user’s GIT and are naturally excreted. When being excreted, the sensor crosses the user’s body boundary for the second time. In our studies, players reported that different from the first-time body boundary crossing, the second boundary crossing was more ambiguous and not voluntary. Some players mentioned that they were not sure about when they excreted the sensor. Although the system told them so, they still felt there was a chance that the sensor was inside their body, which made them be more aware of their body than usual.

This ambiguity was caused by the uncertainty of the “moving” ingestible sensor and also the uncertainty of the human body (for example, the speed of our digestion). In all of our case studies, the sensor moved along the player's GIT and its speed was difficult for players to control. Hence, the time of sensor excretion became uncertain. Uncertainty is often used as a design resource in game design to spark interest [27]. We can confirm this prior theory, as almost all the players in the case studies expressed their interest in knowing the sensor's excretion time before the play. This interest appeared to facilitate spontaneous play. For example, HeatCraft players entered into wagers with their co-players on who would excrete the sensor first. In some cases, this uncertainty of second-time body boundary crossing can also be used as a design material to enrich the experience. For example, the Guts Game required players to play against each other, and players reported that the uncertain excretion time, which determined the game duration, made the competition more playful. When a player's game score was higher than the other player's score, the player with the higher score might want to end the game sooner by eating food that might speed up their digestion. In contrast, players with the lower game score may want to prolong the game to have more time to surpass their co-players.

6.1.2 *Design with the Confronting Material Interior Body.*

The material interior body can be "confronting", as reported by a participant's feedback in the study of InsideOut. According to our case studies, confrontation is not necessarily a negative experience. Players reported that getting to know their material interior body was "violent" yet enjoyable. InsideOut players mentioned that they appreciated the opportunity to see their GIT and felt thankful to get to know more about their interior body. Even though InsideOut offered play modes that made the GIT video more ambiguous and the play experience less "confronting", all players mentioned that they engaged with the original video for most of their play time.

Nevertheless, designers should be aware that confronting experiences are not always a good thing. For example, InsideOut players mentioned that watching the original video of their GIT for a long duration could produce anxiety and stress. Players also mentioned that they switched to play modes that made the video more ambiguous to take a break from the "confronting interior body," especially when they saw "awful" parts, such as the "messy" large intestine containing waste matter that remained after food was digested. According to our interview data, play modes with additional playful elements can help balance the confronting experiences. For example, the InsideOut play mode "Where's Wally?" asks players to tap and "capture" an animated character that moves quickly through the GIT video. In this mode, while the video was realistic and confronting, players were engaged with the gameplay, hence were less confronted by the video. This design strategy aligns with prior intimate data design studies that found that designing humor into bodily interactions can help overcome user taboos and awkwardness [2]. However, designers should note that adding playful elements might lead the player's attention towards the gameplay, rather than the interior body. For example, when playing "Where's Wally?", players appeared to be more focused on the animated character than their interior body.

6.1.3 *Design the Ubiquitous Journey in the Material Body.*

Ingestible sensors are always inside the body before being excreted and hence can potentially support players engaging with their material interior body at any time and any place. The ubiquitous play experiences can help players better understand their interior body. The moving sensor can collect the bodily information in different locations of the player's interior body as it travels through the GIT. This could help players understand the different characteristics of different parts of the GIT. For example, our InsideOut players mentioned that the play let them knew that the stomach wall is smoother than other parts, and the small intestine wall is "fluffier" because of the intestinal villi. Moreover, the ubiquitous play experience can help players understand how their interior body changes at different times across the day. For example, HeatCraft helped players get to know that their body temperature was usually lower during nighttime (sleep) than during daytime.

To leverage the ubiquity of ingestible sensors to fully engage players with their material interior body, it is important to support always-available play. For example, HeatCraft was wearable, and the thermal feedback was always there and unobtrusive. Players reported that they appreciated the heat acting on their body at any time, allowing them to feel their temperature even when they were not paying attention, without disrupting their daily routine. Compared to HeatCraft, the Guts Game did not fully engage players with their material interior body. The game was based on a smartphone, so players might not have been aware of their interior body changes when they were not interacting with the smartphone and actively playing the game.

6.2 The Functional Interior Body

The functional dimension means that the human body can be viewed as a "set of free movements" [42]. This aligns with phenomenology's conceptualization of the body as an embodied consciousness of "I can" [37]. The functional dimension emphasizes the interplay between the body and the world, namely, what I can do to influence the world and how it can influence me. The functional dimension of bodily experience rarely comes to the fore. This is because one usually does not experience the body itself, but things which one's actions deliberately direct one towards. For example, when a person plans to grab a cup from a table, they will usually focus on the cup rather than their arm (as long as their body functions properly).

One usually has limited knowledge regarding the functions of the interior body. Ingestible play can help players get to know more about how they can influence their interior body. Ingestible play can also let players experience their functional limitations. This might help attune players to their functional body, even if they are not able to fully control it.

6.2.1 Design Explorations of the Functional Interior Body.

Ingestible play could support players exploring their interior body functions. In our case studies, player enjoyed exploring how their daily activities could influence their interior body. All the players expressed that after leaving our research lab, they were eager to activate their exterior body to explore how they could control their interior body.

Nevertheless, player's explorations of their interior body might have been hindered because of their limited knowledge of the interior body. For example, if a player did not envision that the interior body data could be affected by physical exercise, the player might not try any physical activity during the play. In our studies, some InsideOut players mentioned that they had not expected they could influence their GIT through physical movement. After noticing the shape changes of their GIT by accident, they began to explore how different body movements could influence their GIT shape. In sum, in ingestible play, players can be motivated to explore their interior body while the players' limited prior knowledge of the interior body might hinder their explorations. Designers should therefore consider how to support players' explorations of their interior body in ingestible play. One way is to embed exploration guidance in the gameplay, and design activities that may influence the sensed interior body data as game actions. For example, we designed the InsideOut video display's rotation and scaling to respond to the player's physical movements (sensed by the iPad), which naturally motivated players to activate their body and raised their awareness that bodily movements could influence their GIT shape.

Designers can also support explorations by supporting communications among players and with bystanders. By supporting communications among players, players can discuss potential strategies to influence their interior body. The Guts Game supported players sending Twitter-sized messages. Players reported that after noticing the co-player had completed a task, they asked the co-player how they did that and followed this strategy to change their interior body temperature themselves. Similarly, with HeatCraft, players were encouraged to be physically together, which supported face-to-face communication. In our interviews, players mentioned that they mimicked other player's bodily actions to change their own body temperature. This co-location and mimicry appeared to enrich player's interactive experience and helped them come up with more strategies to explore their interior body. Supporting communications with bystanders might also facilitate deeper explorations. For example, HeatCraft players mentioned that when communicating with non-playing friends, they gave players suggestions on what to do. Players then adopted these strategies and reported back to their friends how these activities had changed their interior body.

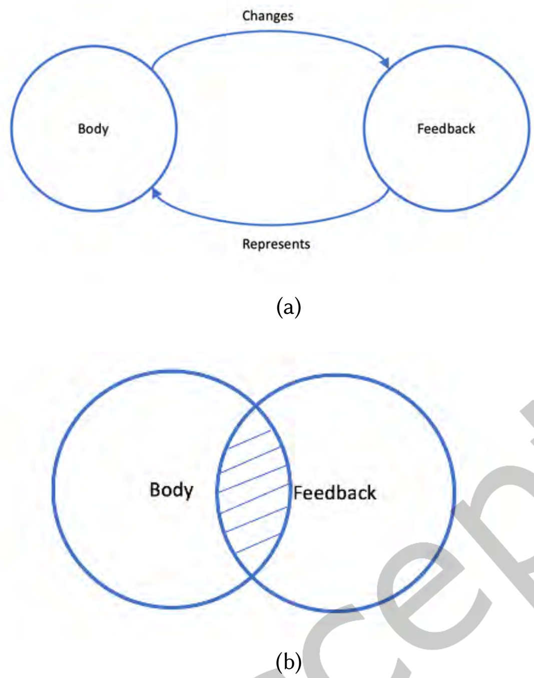


Fig. 8. (a) This relationship between body and system feedback in traditional body games; (b) how the system feedback might be integrated into the player's cognition loop.

6.2.2 Augmenting the Functional Interior Body.

Ingestible play could augment the player's functional interior body. In general, bodily augmentation refers to enhancing human abilities through technology [104]. Here we take a more experiential perspective, discussing how design can augment players' experiential body with ingestible play.

Ingestible play has the potential to let players experience the extension of their bodily capabilities, for example, sensing capabilities. HeatCraft players reported that the system let them feel that they had superpowers to get to know their interior body. This was because HeatCraft integrated the system feedback into players' cognition loop. In HeatCraft, a player shared her story about how she felt the system extended her body: she felt cold during the play, so she drank some ice water to decrease her interior body temperature and thus increase the heating pad temperature to receive the heat. She noted that she then felt strange because one would not normally drink ice water to get warm. The player thought the system augmented how she perceived and used her body.

Compared to the Guts Game, more players of HeatCraft mentioned that they experienced the system augmenting their body. This was because HeatCraft's feedback was integrated into the player's cognition loop. We present Figure 8 to illustrate what we mean by integrating the feedback into the cognition loop. Figure 8a shows how traditional bodily play links the player's body movements to the system's feedback (often shown on a screen). With this mode, players perceive the feedback and then adjust their bodily movements to achieve "better" feedback. However, players may not experience their body as augmented. Figure 8b illustrates how the feedback can be integrated into the cognition loop. In this case, players might experience their body as augmented as they feel that they are the ones who are capable of experiencing their interior body, rather than being informed by an external technology. Therefore, to support augmentation, designers could consider integrating the feedback into the players' cognition loop. This integration might be achieved via the intimacy between the system feedback and the player's experienced body. With InsideOut, the system was physically intimate with the player's body while with HeatCraft, the thermal feedback was psychological intimate with the player's body as heat can be perceived as inside the body and support the perception of felt body [53].

6.2.3 Design with the Dynamic Agency over the Functional Interior Body.

Agency is an important factor in game design as it can influence the players' motivations and also play experiences [118]. Without agency, the game output is entirely out of the player's control, hindering the player's interactions (and turning the experience into a "story"). Keeping a high level of agency is challenging in ingestible play mainly as our agency over the interior body is lower than the exterior body, while the moving sensor can make it even more challenging as players usually could not control the sensor travelling.

Our studies found that the player's agency over the data sensed by an ingestible sensor changed as the sensor moved along the GIT. We take the ingestible temperature sensor used in the Guts Game and HeatCraft as an example. Before swallowing the sensor, the player's agency over the data was high. For example, the player could immerse the capsule into water of differing temperatures to see how the data changes. When the capsule entered the player's stomach, their agency over the data decreased. Meanwhile, the player retained some agency as they could influence the data by drinking water of different temperatures. Nevertheless, the feedback was relatively slow. The player's agency over the data decreased further once the sensor left the stomach and entered the intestine. At this stage, players could barely influence the data through eating and drinking. Players could only influence the data by exercising or through significant environmental temperature changes, such as by entering a sauna. After the sensor was excreted and flushed away, players had no agency over the data.

Therefore, designers should consider how to deal with the players' changing agency over their interior body. The Guts Game players mentioned that the lower agency made it harder to complete game tasks after the sensor entered their intestines. We can envision that the game experience can be improved if we would decrease the game task difficulty when the sensor is located in the player's intestines. InsideOut dealt with the changing agency by providing various play modes. In these modes, their interior body data only influenced peripheral factors rather than the game outcome. For example, in the play mode "Body Balance", the player's interior body video was mapped to the surface of a rolling ball placed on a springboard. Users swung their body to balance the springboard to keep the ball from falling down. With this play mode, the interior body data was shown to players as a game element while the data did not influence the play results, i.e., whether the ball fell down from the springboard. This peripherally focused strategy used in InsideOut is consistent with those found in prior works around biofeedback game design [97]. There can be other strategies to deal with the changing agency. Here we are not aiming to list all the potential solutions, but instead hope to highlight the changing agency in ingestible play as a design consideration.

Designing non-judgmental play might be a way to lessen player frustration associated with low agency. This can be achieved by, for example, using ambiguity as a design material in ingestible play. For example, HeatCraft players mentioned that although they noticed a change of agency across the play, they were not sure about how much the agency changed as the heat sensation was ambiguous. Another design approach is to embrace open-ended play to dampen any such frustration. In comparison, players experienced greater frustration with the Guts Game (more structured, clear game goals to complete) than with HeatCraft (more open-ended, allowing players to freely explore). More specifically, the Guts Game players reported that their agency decreased, and that completing the game tasks became more complex after the sensor entered their intestines. This change caused players' frustration and reduced their motivation to pursue the game goals. In contrast, HeatCraft players mainly reported that they found it interesting to notice the change in agency across the play but did not indicate that the play experience was frustrating.

6.3 The Affective Interior Body

The affective dimension views the human body as a "bearer of sensations" that let us experience our body as ours [42]. We can approach our affective body via localized sensations including touch, pain, proprioception, kinaesthetic and temperature perception. In addition to localized sensations, the affective dimension also includes inner feelings that are inseparable from our body [114].

One might barely experience the affective interior body because of the limited sensory receptors in the interior parts of our body. Ingestible play can engage players with the affective interior body since the sensor inside the body directs their attention inwards to their interior body and evokes various emotions and feelings. Moreover, ingestible play designers can design additional sensory experiences that players might associate with their interior body experience to further engage players with their affective interior body.

6.3.1 Design Interoceptive Activities as a Way to Engage Players with Affective Interior Body.

Interoception is a sense of the internal state of the body. Ingestible play can engage players with their affective interior body by supporting them to "feel" their internal state, like interoceptive activities such as meditations. In ingestible play, the ingestible sensor inside the player's body can serve as a reference point that leads a players' attention back to their body. In all case studies, participants suggested that having the ingestible sensor – a foreign object inside their body – encouraged them to periodically think about the sensor and, consequently, about their interior body. When players thought about the sensor, they tended to imagine how it was moving inside their body. For example, a player of HeatCraft mentioned that when he experienced small random pains in his body, he wondered what the sensor was doing and imagined how the sensor was tumbling over and pushing the intestines' wall. Moreover, since the sensor's location was ambiguous, players might try to "feel" the sensor and their interior body, which was similar to body-scan meditation [82] that can engage people with their affective body.

Leading players' attention inwards provides a basis for interoceptive activities. This could be achieved by motivating the players to "feel" the sensor moving and imagine how their interior body works. In both Guts Game and HeatCraft, the sensor's location was unknown, which gave players room to imagine how the sensor was moving. InsideOut gave less room for imagination because it provided visual information on the GIT filmed by the sensor. We designed playful elements that related to the interior body to guide players' "inwards imagination". For example, we designed rumbling sounds into one of the InsideOut play modes to stimulate the player's imagination of the GIT being cramped and generating sound when the capsule hit the GIT wall. This design might have helped players to imagine interior body information that they could not sense by themselves.

External sensory stimulation can also lead a players' attention inwards. While both Guts Game and HeatCraft used the same ingestible sensor, HeatCraft players mentioned more about their bodily experiences, and the Guts Game players reported more about their temperature data changes and their game behaviors. We believe this difference arose because HeatCraft's thermal feedback engaged players more with their body sensations and hence their affective body. In our studies, HeatCraft players reported that the thermal stimuli directed their attention back to their body and facilitated inward-looking. This result aligns with prior works in somaesthetic design that uses thermal stimuli to direct the attention inwards to increase self-awareness [49]. Such a strategy of using sensory stimulation to lead the attention inwards has also been used in current bodily play, e.g., by guiding certain body movements or producing localized bodily sensations to attract the players' attention to their first-person bodily experience and ultimately increase players' body awareness [22, 77, 86]. However, designers should notice that not all the sensory experiences could lead players' attention inwards. Jonsson et al.

[53] suggested that subtle heat acting on the body can be a promising modality for leading attention inwards compared to other modalities such as vibration that is perceived as something external to the body.

6.3.2 Design a Sense of Ownership towards the Represented Interior Body.

Facilitating the players' ownership towards their sensed bodily data is usually a basis for players to engage with their own body in body-centric design [99]. Only if users experience a sense of ownership towards the system's feedback, will there be a solid motivation to further engagement to achieve bodily understanding [99].

Such a sense of ownership might be more challenging to facilitate in ingestible play compared to other types of games. In current body-centric interactions, a user's body movements might be represented ambiguously and artistically [103] but these representations do not hinder users' understanding because they are familiar with the exterior body shapes and movements and hence can easily associate the representations with their body. On the other hand, without technological intervention, most people have only a very rudimentary understanding of their interior body. Consequently, in ingestible play, the player may struggle to associate the representation with their own interior body. Indeed, our case studies confirmed that players sometimes were uncertain whether the ingestible system accurately revealed their interior body status. For example, HeatCraft players mentioned that they expected additional feedback, and they hoped to have an LED or alike to show whether the system was operating reliably.

To support the sense of ownership, designers can consider facilitating a conceptual link between the feedback and the interior body. For example, designers can consider the location of the feedback to support a conceptual link between it and the sensed interior part's location. In InsideOut, we placed the feedback display around the player's stomach area, in a similar location to their GIT. This placing helped players to quickly build a conceptual link between the feedback and their GIT, encouraging a feeling that their body had become "transparent".

Another way to facilitate a conceptual link between the feedback and the interior body is by designing the feedback as an analogy to the interior body data. For example, in HeatCraft, we designed thermal stimuli that acted on the players' exterior body in a way that was analogous to the players' interior body temperatures. While players could not feel the warmth or coldness of their interior body in the same way that they felt their exterior body, they could more easily connect the thermal feedback with changes in their interior body temperature.

6.3.3 Design for Reflections to Deepen the Engagement with the Affective Interior Body.

Reflection is "reviewing a series of previous experiences, events, stories, etc., and putting them together in such a way as to come to a better understanding or to gain some sort of insight" [9]. Reflection can help players gain a more complete understanding of their interior body, hence deepen their engagement with their affective body. In all case studies, players reported on their reflection experiences. Table 1 shows how ingestible play might support the five levels of reflection presented by Fleck et al. [34].

Design choices can better support players' reflections on their interior body. For example, our systems supported social interactions, which helped facilitate dialogic reflection as players were asked about their game strategies and their findings regarding their interior body. Also, critical reflection could be facilitated via critical design (i.e., the design that reveals the design ethics and values) [7]. In our case, showing a player's realistic GIT video to others provoked players to consider their interior body data's privacy.

6.4 The Social Interior Body

The social dimension highlights that other people's gaze can influence our bodily experience [42]. This was in line with Sartre's argument [108] suggesting the gaze of others can lead to bodily objectification and alienation. Slatman [113] also proposed that cultural and social contexts can influence the social dimension of the bodily experience. For example, the color of one's skin influences how one orientates oneself in the world even though the skin color has no impact on one's bodily capacities [1].

Reflection level	Meaning	Ingestible play behaviors
R0 Description	Description of events without explanation.	Players get to know their interior body data via the system.
R1 Reflective Description	Description including justification or reasons for action or interpretation, but in a descriptive way.	Players try to understand why their interior body data changes.
R2 Dialogic Reflection	Looking for relationships between pieces of experience or knowledge, evidence of cycles of interpreting and questioning, consideration of different explanations, hypotheses and other points of view.	Players explore various factors that influence their interior body data.
R3 Transformative Reflection	Revisiting an event with the intent to reorganize or do something differently.	Players modify their actions to further explore their interior body.
R4 Critical Reflection	Where social and ethical issues are taken into consideration.	Players consider the ethical and social issues related to ingestible play.

Table 1. How ingestible play can support players' reflections. The first two columns are the five levels of reflections [34], and the last column shows the players' behaviors related to the levels of reflections based on the user studies.

In general, one can barely experience the interior body's social dimension since others cannot see nor have access to one's interior body. However, ingestible play has the potential to augment the social dimension of the interior bodily experience. For example, ingestible play can sense the player's interior body data and show it to co-players.

6.4.1 Design Subversive Experience to Engage with the Social Interior Body.

Ingestible play is subversive in nature. In our studies, most of the players mentioned that although they personally felt excited about having ingestible sensors for play, they were worried about how others might feel about this. Swallowing a digital device for non-medical purposes is generally considered to be against social norms. Therefore, some players mentioned that they wanted the external play technologies associated with the sensor (e.g., data recorder) to be smaller and less conspicuous. With the Guts Game [71], two participants out of 14 mentioned that they did not want to wear the data recorder as it was cumbersome and not fashionable. With HeatCraft [53], eight participants out of 14 expressed their concern of wearing the belt in public. They thought wearing a belt with data recorder and other electronics made them looked conspicuous in public. With InsideOut [75], no participant reported experiencing a stigma in public. It might be because that players reported that they only wanted to share their play experiences with family members and close friends who might not feel uncomfortable about it, for example, an InsideOut player reported that he did not share his video with his mum as he thought his mum might feel discomfort. Without the video, the backpack and also the black screen on the T-shirt did not look that conspicuous. Despite the potential of experiencing stigma when wearing an ingestible system, players also thought sharing this unusual and interesting ingestible play experience with others made them become more connected with others. Hence, we believe that the subversive experience can be a design material in ingestible play while designers should also be conscious of such experiences in public spaces. Ideally, ingestible play could support subversive experience to some extent without making both players and bystanders uncomfortable.

To leverage the subversive nature of ingestible play, designers could consider the public aspects. Designing the interior body data to be more public might blur the boundary between the "public" exterior body and the "private" interior body, providing an opportunity for engaging with the social dimension of the interior body. For example, InsideOut publicly displayed the player's interior body video on a screen worn in front of their body, which support facilitating subversive play experiences. However, an intense subversive experience might bring about negative effect. To deal with this, InsideOut gave players control over the display by having play modes that supported ambiguous visualizations, and by adding a button which allowed the player to hide the display's content.

6.4.2 Design Resonation to Engage with the Social Interior Body.

In sociology, resonation refers to our relationship with others and the world [106]. Here, we use "resonation" to speak to our relationship with our own and others' interior bodies. Prior work in HCI has explored designing resonating experiences to engage people with others' body. For example, Aslan et al. [6] designed a tangible artificial heart to vibrate based on one's partner's heartbeat to facilitate resonating experiences. Ingestible play could similarly support this bodily resonation to engage players with their social interior body.

Without technology intervention, we would know very little about others' interior body status. With ingestible play, players can appreciate the resonating experience of knowing their co-players' interior body information. In our studies, players shared their interior body information with others including the sensed data, the digestion information, and even the time at which they went to the toilet. The study results showed that such resonating experiences facilitated engaging social ingestible play experiences, which made them feel closer to their co-players [71, 75, 76]. Moreover, knowing their co-player's interior body information could further increase the players' awareness of their own interior body as they might want to compare and share their bodily information with others. Consequently, the social resonation further engaged our players with their own interior body.

Designers can consider designing data sharing to support resonating experiences. Although the Guts Game players could not directly see each other's temperature data, when their co-player finished a game task, they could receive system messages containing information about their co-player's body temperature. Also, InsideOut players could show their GIT video on the screen so that everyone around them could see the representation of their interior body. Similarly, HeatCraft players and bystanders could touch the player's belt to feel the temperature, indicating that player's body temperature. Indeed, players of HeatCraft mentioned that they enjoyed exchanging their belts with each other to experience each other's body temperature. These design choices and players' reports demonstrated the efficacy of data sharing in facilitating resonating experiences in ingestible play.

Another way to facilitate resonation is to support others (including co-players and game bystanders) to interact with the player's interior body. For example, when designing HeatCraft, we included sensory feedback that others could also experience by putting their hand on the player's stomach. Localized sensory feedback such as haptic and thermal feedback is not as public as the visual display of data, because others can only experience the player's intimate interior body when they are allowed. Intimate social experiences can also be facilitated by designing the interior body information as a game element. For example, in the InsideOut "Finding Wally" play mode, the player's GIT video is turned into a game element (i.e., the game background), and others can tap an animated character that moves quickly in the video. Some players mentioned that they only wanted close friends and family members to play this mode because they "felt" others were touching their interior body when tapping the GIT video displayed on the front of their body.

6.5 Summary of the Framework

In this section, we have presented our design framework of ingestible play. The framework was constructed based on the four dimensions of bodily experience. In general, we found that, without medical training, our experience with the interior body is limited as it is mostly invisible and inaccessible, and hence we have limited knowledge of our interior body. However, ingestible play can be designed to augment our experience with our interior body. We hope this presented design framework can serve as a starting point to guide designers to design ingestible play to enrich players' experience with their interior body.

Whilst, for the purposes of this paper, we analyze each dimension individually, we do not propose designers to split bodily experience into four separate parts when designing and evaluating bodily play. Rather, our framework is presented to assist designers to take each dimension into account without forgetting that they are tightly intertwined [42].

7 DISCUSSIONS AND FUTURE WORK

In this section, we first discuss how our work is situated within current related works and then present our understanding of the possible future research directions of ingestible play.

7.1 Extending the Magic Circle of Play to the Interior Body

Our works could help us better understand how ingestible sensors can extend the current bodily play genre. Huizinga proposed the term "magic circle" to explain play: to play a game is to step inside a magic circle with specified rules [50]. In other words, the play takes place in a separate time and space, which is governed by certain game rules. The concept of "magic circle" has been widely used to explain play, however, the concept needs to be expanded when it comes to pervasive games. Montola proposed that a pervasive game is "a game that has one or more salient features that expand the contractual magic circle of play socially, spatially or temporally" [83]. This is because unlike traditional play where players play in certain spaces and at certain times, pervasive games can occur at any time, in any place, and anybody can become a player.

Our work is in line with Montola's definition of pervasive games [83]. Ingestible play expands the digital play spatially. Due to the pervasive nature of the ingestible sensor, i.e., the sensor is always inside the user's body before being excreted, the three projects might turn any place the player inhabits into a playground. Ingestible play also expands the digital play temporally. Considering the ingestible sensor might be inside the player's body for days, the play session can be integrated into the player's ordinary life. In addition, with ingestible sensors, players experience playful experiences of thrill and subversion when engaging with the sensor, which indicates that the play can already begin when players are about to engage with the play technology rather than when players interact with any designed digital content. Regarding the social interaction dimension, with ingestible play, players might interact with bystanders during the play, and these interactions might affect the player's play actions and bodily experience. For example, in our studies, some players followed the bystanders' suggestions on how they might influence their interior body. This shows that ingestible play also expands the play socially.

In addition to Montola's definition [83], our work showed that ingestible can take a step further to expand the magic circle corporeally. Salen and Zimmerman [107] emphasized that it is the player who creates the magic circle. The game does not exist if players do not adopt a playful attitude. This argument indicates the corporeal dimension of the magic circle. If play happens, there must be someone entering the circle and performing play actions. Without the corporeal dimension, the magic circle would be meaningless.

Our work shows that ingestible play extends the boundary of the magic circle's corporeal dimension to the interior body. Once the player enters the magic circle, the play "discloses" the player's interior body. To engage in ingestible play, players activate their exterior body to influence the interior body. Any change in the interior body data sensed by the ingestible sensor influences the game feedback, which can further motivate players to explore their interior body.

Our analysis based on the magic circle theory helps situate our work as a new play genre. Next, we will discuss how our framework relates to prior works in HCI and also speculate upon future research from three aspects, i.e., technology, design, as well as cultural and ethical issues.

7.2 Technology

Bodily-integrated technologies including ingestible sensors are still in their infancy and the use of most bodily-integrated technologies are limited in the areas where they were originally developed for, e.g., for medical areas. Therefore, we have limited knowledge regarding the bodily-integrated technology's design for interaction/play purposes.

Heffernan et al. [45] summarized reasons for hobbyist use of insertable devices, i.e., "Desire for a New Body Modification", "Wanting to be a Part of The Next Big Thing", "Extending Human Function and Capabilities", and "Tiring of Wearables". Our work also found that players voluntarily participated in ingestible play as they appreciated the human-technology integration and body augmentation. Regarding the "Tiring of Wearables", our participants similarly expressed that they appreciated the opportunities afforded by ingestible sensors to make their body an interaction "interface", rather than the play technology itself. However, participants cannot truly experience removing wearables with the existing ingestible sensor technology. Currently, a user needs to wear a data recorder to receive data from an ingestible sensor, which can be cumbersome. Future work could explore how ingestible sensors could be designed without the need for wearable recorders but instead be connected to other bodily-integrated interfaces such as skin interfaces [94].

The existence of wearable data recorders also limits possible interaction scenarios. For example, players may not enjoy ingestible play in swimming pools, where devices can get wet. Our work showed that "ubiquity" is an essential design theme in ingestible play to engage players at any time and any place and also support players' exploring their GIT as the sensor moves. Similarly, in Mueller et al.'s work of bodily-integrated play [88], the authors emphasized the opportunities of always-available bodily play afforded by body-integrated technologies. However, the current ingestible systems might fail to make full use of the sensor's ubiquity. In some cases, the sensor might run out of battery before being excreted (like in our case study InsideOut [75]). Hence, designers can explore how to prolong the battery life of ingestible sensors to support a longer duration of ingestible play. New ways of powering the sensor can also be investigated, for example, by charging the sensor via devices outside the human body [33].

At the same time, we acknowledge that the above technological limitations of ingestible sensors might bring about intriguing design opportunities. Benford et al. [11] explored how designers could deal with uncertainty in interactions. Except for removing or hiding uncertainty, designers could also reveal and exploit uncertainty to promote users' exploration and interpretation. Similarly, Gaver et al. [39] presented design tactics for embracing ambiguity as design resource to encourage users' reflections and evoke new beliefs and attitudes. In our work, if we take a common viewpoint that ambiguous interfaces should be avoided, the wearable data recorder and the sensor's limited battery life might hinder the players' ubiquitous engagement with their interior body. However, if we consider exploiting uncertainty and ambiguity, we might find new approaches for engaging people with their interior body with ingestible sensors. For example, with ingestible play, we can motivate players to explore the uncertain disconnection between the sensor and data recorder, which might motivate players to reflect on how their embodiment might be influenced by the bodily-integrated technology. This tactic is also in line with the user experience of our study. In the Guts Game study, players expressed their finding that electrical interference might cause disconnections between the sensor and the recorder. With HeatCraft, players described how they exploited the disconnection as a resource for play: one player swallowed the sensor and the other player wore the associated recorder so that they could not be far away from each other to keep the data streaming. Similarly, the limited battery life of the sensor could also be used to facilitate bodily engagement. After the sensor runs out of battery power and the system stops updating data, we could guide players to consider the location of the sensor by providing localized bodily sensations. This might facilitate the "interoception" experience, as per our framework.

Future ingestible play might also consider how ingestible sensors can afford interactive outputs. Holz et al.'s work [47] explored how implanted user interface could afford digital outputs including LEDs for visual feedback, microphones for providing sound, and vibrators for providing haptic experiences. Meanwhile, current ingestible sensors on the market can only be used for input by collecting body data while they cannot provide output directly: they use a data recorder to provide output. Holz et al.'s work [47] inspired us to consider the possibility of having ingestible sensors provide outputs. For example, we hoped to have ingestible sensors that could generate playful sounds inside the GIT. Also, sensors that can perform actuating functions such as providing haptic feedback might also offer intriguing sensory experiences to players. We speculate that the lack of these functions is due to the absent of different stakeholders in the ingestible sensor development process. Current ingestible sensors were designed for medical purposes rather than interaction so there was limited need for having outputs. In contrast, there are plenty of hobbyists using implanted devices for play. Therefore, in the future, we might think beyond medical contexts, needs and applications during ideation processes for sensors. Conducting participatory design sessions and involving game designers and potential gamers when developing future ingestible sensors might facilitate the emergence of innovative playful ingestible sensors.

7.3 Design

Design knowledge around ingestible play is limited. Below we consider our works in relation to three key areas in the field: bodily-integrated interactions, interactions with a focus on the interior body, and social bodily play.

7.3.1 Design Bodily-integrated Interactions.

Emerging bodily-integrated technologies have not been widely used in interaction design while we can still see some attempts in the field. Byrne et al. [21] used galvanic vestibular stimulation (GVS) to facilitate vertigo experiences, which was utilized as a design material for bodily play. Lopes et al. [79] used on-body electrical muscle stimulation to actuate a user's wrist to aid hand drawing. These bodily-integrated systems extended the way how users naturally receive digital information via localized body sensations. In contrast, by introducing ingestible sensors to interaction design, our work extends the way how users input information to interactive systems. With ingestible sensors, we now have an opportunity of using real-time interior body data as interaction input. This could either help technologies understand humans or help users better understand themselves, especially the interior parts of themselves.

7.3.2 Interaction Design with a Focus on the Interior Body.

As we mentioned previously, there are design works with a focus on the interior body that externalized information from the interior body [15, 36]. These works showed that people can be eager to know about the interior body and demonstrated the potential of externalizing the interior body in improving one's body literacy. Our work confirms these results as our participants enjoyed getting to know their interior body through play. In addition to this, our work showed that people enjoyed exploring their interior body through bodily actions including eating, drinking, and moving. This was in line with prior works emphasizing the coupling between sensing and representing the interior body changes when designing interactions for increasing one's interior body understanding [98].

Meanwhile, in most of these prior works, the interior body being externalized was not the user's own body. Therefore, these works fell short in highlighting the first-person experience of engaging with one's own interior body. Our work extends these works by highlighting the "affective" dimension of the interior body. By having an ingestible sensor physically entering the body, players could become more engaged with their "affective" interior body as the intracorporeal sensor could facilitate voluntary interoceptive activities (e.g., players tried to feel the sensor location and imagined the sensor moving in our case studies). The "affective" body can also be highlighted via bodily sensations [114]. Although we have limited sensory receptors in our interior body, on-body localized sensations as system feedback could be an alternative to help naturally understand our interior body status. For example, Norooz et al. [98] presented an e-textile shirt that visualized physiology data on the fabric, mainly via LED (visual) and sound. In future work, we can embrace localized sensations such as haptic and thermal experiences to simulate the interior body sensations in order to engage people with their "affective" interior body. In sum, our work highlights that when externalizing one's interior body, we should also consider the exploration affordances of the system and also putting the "affective body" in a more central role, addressing questions such as: how can interactions be designed to make users more intimate with their interior body?

7.3.3 Design Social Bodily Play.

In addition to the "affective body", our work highlights that ingestible sensors could bring about novel design opportunities for social body games. Mueller et al. [90] presented a framework to guide designers in taking a social perspective on bodily play. By comparing our results with this framework, we found how ingestible play extends the current social experiences in bodily play. According to Mueller et al. [90], designers can use the body's malleability to intertwine multiple bodies. One typical example is a "3-legged race" where two players run hip to hip and use a strap to tie together their right and left ankle respectively. Similarly, our work shows that not only extending the body boundary can be playful, penetrating the boundary, both absorbing and excreting can also be used for bodily play design. However, our work does not highlight this body boundary penetration in social play design much (only by letting players experience the swallowing together). Future work might consider how this penetration can be designed for multiple intertwined bodies. Mueller et al. [90] also suggested supporting bodily mimicry and connecting one player's movement with another player's sensation, which was in line with our design theme "resonation". With ingestible play, we can not only support participants mimicking each other's movements, but can also support them in exploring how their interior body responds to the same activities. In sum, our work shows how ingestible play might relate one's interior body to others'. Future work could also explore interaction design at a more significant societal level. For example, if everyone has a sensor inside their body in the future, could the sensor be designed to support social interactions among citizens? Would this change the way we interact with each other?

7.4 Ingestible Play, Culture and Ethics

Our work has presented ethics considerations during our design and study process. Our considerations speak to informed consent, data privacy and risk management. Although we did not present a full discussion of ethics issues of ingestible play, we believe our work extends current ethics research around intracorporeal devices in medical contexts [40, 44, 59] as we discussed the ethics of using ingestible sensors as an interaction design material. Such a discussion could also serve as a basis for further works exploring ethical and cultural issues associated with interactions with intracorporeal devices for non-medical purposes.

In addition to our practical considerations when conducting ingestible play research, we believe that there is a need to start a critical reflection on the social and ethical aspects, which is also in line with recent advocation on more engagement with ethics under the third wave of HCI that focuses on culture and experience [12, 14]. Beyond the risks such as sensor retention on the individual level, we might envision the potential risks on a broader level if ingestible play becomes commonplace in the future. First, ingestible play might shape the public understanding of the human body. Prior works indicated that the ubiquitous presence of the interior body in public media might shape the broader societal views of the human body, e.g., leading to people perceiving invasive surgery as harmless [119]. Moreover, an increased level of body transparency might lead people to inaccurately believe that "seeing is curing", which is not accurate [119]. Therefore, in future designs of ingestible play, designers might seek responsible design solutions to let players step towards a more complete understanding of the human body. For example, by embracing the affective dimension of the body, as per our framework, we can engage players with their "lived" interior body. By doing so, players could treat any augmentation of their interior body more seriously as the interior body is a part of their lived body rather than an object that can be easily manipulated. There might also be equity issues. Considering the cost and single-use aspect of the ingestible sensors, some people can afford to play ingestible games frequently, while some people might not. Sustainability is another issue designers might need to be aware of. In our studies, players mentioned that the sensor was single-use and was hence flushed away, and they were not sure about the impact on the environment. We envision that in the future, food-based electronics might emerge [31, 122], resulting in the opportunity for designers to use them as sustainable material to facilitate ingestible play, which might dampen the potential negative social impact of ingestible play.

Despite the potential risks, we believe that there is a need to explore the design of ingestible play. Ingestible sensors are currently primarily used in medical procedures. Designing ingestible play has the potential to engage these patients with the medical procedure, improve the user experience and dampen their potential anxiety during the process while increasing the acceptance of the technology. Moreover, as our work indicates, ingestible play has the potential to engage people with their bodily data, and increase their bodily awareness, bodily knowledge, and health literacy. Furthermore, exploring the design of ingestible play can help refelect on the potential risks and benefits of ingestible sensors, helping to prepare for a future where ingestible sensors become commonplace. In recent years, we could observe an increasing number of people enjoy "hacking" their bodies. This could be seen from the art projects that involve body modifications [110], and also the cultural movement of Do-it-yourself biology where hobbyists hack their own body for entertainment, life extension, education, etc. [63]. With ingestible sensors becoming more popular, there might be more and more people using the sensor for non-medical purposes, e.g., for games and play. Therefore, understanding interaction design around ingestible sensors at this stage might help us step towards a more humanized and responsible technology future for ingestible sensors.

Our work could also be a basis for future research exploring the cultural effects of bodily-integrated interactions. For example, ingestible play can challenge and extend the current interaction space in body-centric interactions. Chen et al. [26] divided body-centric interactions into three types based on the distances between body and interactive technology, i.e., personal space, peripersonal space, and extrapersonal space. Similarly, Mueller et al. [95] used proximity, i.e., the interpersonal distance between players and devices, as a design material for bodily play. Our work extends prior research by letting designers consider the design space of the interior body and how intracorporeal devices challenge the current body-technology relationships. The body artist Stelarc argued with his artwork "Stomach Sculpture" that the human body can be experienced as "hollow". We can simply see our body as something hollow and hence regard our mouth and anus as an entrance and exit for the interior body space. If we take this radical perspective, how can we design for this "innerpersonal space"? How can we reconsider our proximity with interactive technology? How can our social experience be augmented by connecting our interior body with each other's? In addition to the cultural aspects of proxemics, many other cultural issues could also be considered around the interior body in future research. For example, future work might explore how culture shapes our understanding of our interior body. Potential questions could be: how does culture influence our acceptance of intracorporeal devices; and how might the advancement and popularity of intracorporeal devices shape our culture?

8 LIMITATIONS

This section discusses the limitations in our work.

First, our design framework was derived from our three case studies that were designed by our research team. Having more designers and HCI researchers designing ingestible play could improve our understanding of ingestible play.

Second, our work only involves two kinds of commercial ingestible sensors as play technologies. Having more case studies that use other sensors might enrich our design framework. For example, in all three case studies, the ingestible sensors we used did not provide location information, so the players in the studies did not know the sensor's exact location inside their body. This ambiguity of the sensor location could direct the players' attention inwards to their interior body as players tended to "feel" where the sensor was. However, such inward-looking experiences might fade if future ingestible sensors can provide users with location information.

Third, our work adopted the RtD approach, so our knowledge contribution is based on the designs and user experiences of the three case studies. We acknowledge that additional case studies might add more details to our framework. For example, in the three case studies, the feedback modalities we have used include visual, thermal and sound feedback. We did not use modalities such as smell and taste. Future research might explore how multi-sensory experiences can be designed to enrich the ingestible play experience.

Fourth, our work aims at understanding how ingestible play can facilitate bodily engagement, so we turn to Ginfelde's phenomenological work to better analyze bodily experience. We encourage future work to also consider ingestible play in relation to other theories, including HCI design theories, and also theories outside HCI, like Slatman's understanding on the body [114]. Such theory-inclusions will extend our work and provide a more thorough and deeper understanding of ingestible play.

Fifth, our design framework still lacks other designers' validation. A long-term study in which game designers use the framework to build ingestible play systems may help improve it.

Sixth, our work did not intend to motivate people to use ingestible devices for play. We acknowledge that some people feel uncomfortable using invasive technologies or getting to know interior body information. In all studies, we only recruited volunteers. Consequently, we did not obtain data to allow us evaluate how designers might motivate people to engage with ingestible play. Nevertheless, our studies shed some light on this design challenge. For example, the Guts Game players reported that both the game narratives and the presence of their co-player helped them relax before swallowing the sensor. Future work could be undertaken to investigate how design might motivate players to participate in ingestible play. Furthermore, we believe that people will be more accepting, both of the technology and of ingestible play, as ingestible sensor technology come into more common use. We also anticipate that the media might help popularize ingestible play. As a comparison, we no longer consider X-ray and CT scan images confronting because we seem them so often in the popular media [119].

Seventh, our work only involved people who are interested in ingestible play and provided an initial understanding of their motivations to participate in the study. In the future, we can conduct a more complete empirical study to understand their play motivations. Moreover, we can explore why certain people feel uncomfortable to play with ingestible sensors.

Eighth, we acknowledge that there are art projects around ingestible sensors (see section 2.4) that we did not use for building our framework. The major reason was that these art projects were presented by body artists to express their understanding of the human body, which lacks detailed user experiences for us to analyze. Moreover, these works were usually provocative designs that challenge traditional body concepts, while not necessarily built for facilitating bodily play and engagement, hence discussions around these artworks are beyond the scope of this work. Meanwhile, we still find that the design of these artworks could fit our framework, or at least in part. For example, Stelarc's work of video recording the insertion of a self-built ingestible sensor [115] highlights the material dimension of the interior body, and the design of the artwork is in line with the design recommendation presented in our framework. This artwork showed the audience "confronting" interior body video as the sensor moved along the artist's GIT, aiming to motivate the audience to reflect on the role of the human body with the development of technology. The artist expressed his understanding that the human body is "hollow" and can be a host for technology with this work. Similarly, our framework suggests designers consider designing with body boundary and the confronting interior body when engaging players with the material dimension of the interior body. Different from Stelarc's work, Poope's work Audiopill [52] highlighted the affective dimension of the interior body. The work enabled people to experience music beats from the inside of the body, which was similar to our design recommendation that suggests designers create interoceptive activities to engage players with their affective interior body. Hatoum's works focused more on the social dimension of the interior body: as the audience entered the cylindrical space where a video of the artist's interior body was displayed, they became foreign bodies entering the artist's body [10]. This design was similar to our design recommendation that suggests designers create resonation to engage players with the social interior body. We acknowledge that some of these artworks are provocative designs that engage people with the interior body in a rather radical way. Such a radical dimension is not included in our design framework. For example, except for the social dimension, Hatoum's works also hoped to express the artist's concerns regarding surveillance, letting people reflect on the violent appropriation of imaging technologies. In the future, we might involve more artworks and provocative designs around ingestible sensors to improve our design framework.

9 CONCLUSION

Inspired by the trend of HInt, we believe there is an opportunity to use technologies that are physically integrated with the human body to facilitate novel play experiences that engage players with their interior body and support them to gain a more complete understanding of their body.

This work explored a design space of ingestible play which we define as bodily play that uses ingestible sensors as play technologies. To carry out our exploration, we designed and developed three playful systems based on ingestible sensors. We conducted a user study in real-world settings to understand each system's user experience. By combining the study results and our reflections on the design process, we have developed a design framework for ingestible play, discussing design implications from four dimensions of bodily experiences, i.e., the material body, the functional body, the affective body, and the social body.

We hope that our work will inspire and guide the future design of ingestible play. More broadly speaking, we hope that our work will encourage interaction and game designers to consider how novel intracorporeal devices can bring about novel design opportunities in digital play. Furthermore, we hope to motivate designers to anticipate how the trend of HInt might change the way we can play and interact with our bodies. Ultimately, our work aims to expand the ways in which the design of more humanized, bodily-integrated technologies can playfully engage people with their body.

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