ChewIt. An Intraoral Interface for Discreet Interactions

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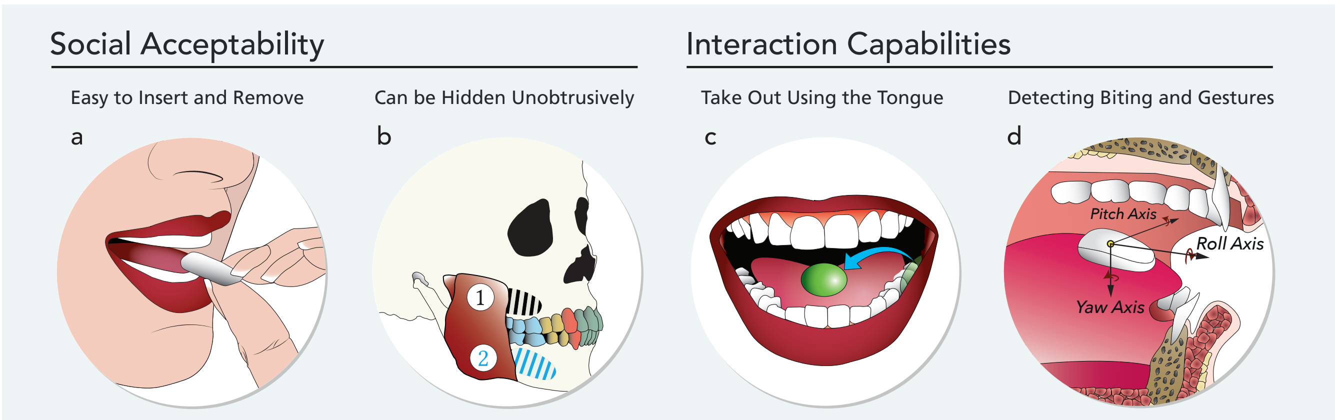

Figure 1: ChewIt is a novel intraoral interface, similar to a chewing gum, offering new ways of discreet, hands-free interaction.

ABSTRACT

Sensing interfaces relying on head or facial gestures provide effective solutions for hands-free scenarios. Most of these interfaces utilize sensors attached to the face, as well as into the mouth, being either obtrusive or limited in input bandwidth. In this paper, we propose ChewIt – a novel intraoral input interface. ChewIt resembles an edible object that allows users to perform various hands-free input operations, both simply and discreetly. Our design is informed by a series of studies investigating the implications of shape, size, locations for comfort, discreetness, maneuverability, and obstructiveness. Additionally, we evaluated potential gestures that users could utilize to interact with such an intraoral interface.

CCS CONCEPTS

• **Human-centered computing → Interaction devices**;

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KEYWORDS

Intraoral Interface, Hands-free, Input Device, Interaction Modality, Discreet Interaction, Reflexive Interaction

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1 INTRODUCTION

Researchers have proposed a variety of hands-free interactions [5, 9, 77], contributing to a greater efficiency in multitasking [82]. In addition, they have also proven to be useful when applied as assistive technologies [30, 34, 45]. This significantly helps people with physical impairments to regain essential interaction capabilities, in particular patients suffering from locked-in syndrome [69]. While these interfaces can be useful for people with special needs, they are usually cumbersome and disruptive [43, 46, 57, 63, 90]. Particularly these two limitations prevent healthy people without special needs from adopting these new interaction interfaces. In contrast, potentially socially acceptable technologies offer only a very limited input bandwidth [54, 55].

We investigate a novel intraoral ("in-the-mouth") non-attached input interface, ChewIt, to strike a balance between social acceptability and a high input bandwidth. ChewIt provides discreet interactions, as users are able to hide the device inside the oral cavity. We exploit the well-pronounced dexterity of the tongue in conjunction with the jaw, teeth, and mouth cavity, to enable new input opportunities.

To gain a better understanding of the peculiarities of discreetness and general feasibility, we initially ran a series of user studies (Study 1: spectator's perception, S2: user's perceived obstruction, S3: understanding habits and limitations). Based on the results of these evaluations, we continued investigating potential intraoral interface designs through a further series of studies (S4: implications on dimension, S5: comparing shapes, S6: volume factor, S7: defining gestures). Informed by these investigations, we developed a prototype system, ChewIt.

In summary, the main contributions of this paper include the design, implementation, and validation of a non-attached intraoral interface.

2 RELATED WORK

Oral Input Interfaces

Speech Interfaces: Systems which utilize speech interfaces, such as intelligent personal assistants [12] or cognitive assistants [21] are gaining popularity. Some examples include Siri [41], Alexa [2], and Cortana [11], which are embedded into smartphones, computers, and standalone devices. This input modality successfully provides assistance when the hands are occupied with a primary task, such as driving and making a call. However, its drawbacks are in creating disturbances for others [20] and compromising privacy concerns.

Tackling this, Silent Speech Interfaces (SSIs) [17] are introduced aiming to maintain privacy, making speech interfaces more acceptable in public spaces. A great variety of different technologies [48] have been utilized, such as ultrasound [16, 18], video imaging [35–38, 76], audio [25], neuromuscular activity [43], electromyography [84], and electromagnetic motion [28, 85]. SSIs are also useful in environments where surrounding noise inhibits audible data, as well as beneficial for people with speech impairments [22, 29], who cannot use their own voice. However, current SSIs also yield a number of drawbacks. For instance, most interfaces are either intrusive [85], obtrusive [84], or require excessive processing times [37]. Apart from these technical issues, speech assistance yields a high memory burden and creates a disproportional cognitive load, for instance having to speak out a sentence when only a binary change is required [10].

Mouth Gesture Interfaces: Alternative mouth gesture interfaces have been introduced that enable a quick input mechanism, for instance controlling a computer with a simple sip and puff [62, 63]. Such interfaces rely on diverse technologies, such as gnathosonics [83, 86, 87] and audio to recognize the sound of tooth touches [47] to implement clicks [4, 59]. Other technologies to detect mouth gestures include optical sensing [15, 31, 52], air pressure changes [3], microradar data [49], infrared [7], and EMG [90]. These interfaces provide a significant benefit for people with special needs, namely those experiencing limited mobility, and for applications that require of additional input [73]. However, as these interfaces are all externally attached, they are highly noticeable by others and thereby limit social acceptability among those not requiring special assistance.

To overcome these issues, semi-invasive approaches have been proposed, including a swallowed probe [32] and an in-ear-placed sensor [50, 53, 55]. In addition, invasive technologies, such as an RFID chip under the skin [33], piercings with magnets [39], and a tongue-glued magnet [70] have been investigated in research.

As social acceptability of implantable technology may be questionable, we focus on semi-invasive technologies that can be easily removed by the users themselves. These semi-invasive mouth gesture interfaces are often used by people with physical impairments, such as Jouse [42] and IntegraMouse [40]. Most of these interfaces are comprised of two or more separate parts, in which one is placed inside the mouth [39, 46]. Although these interfaces enable great input mechanisms, most are either located on the palatal vault space [64, 71, 72, 74, 75, 81], at the buccal shelf area, or at the lower jaw [67], also creating speech impediments.

User Acceptance of Technology

Social conventions [26] and context play an important role in the prevalence and acceptance [14, 27, 58] of novel technologies. As previously stated, using a speech assistant such as Siri [61] in public or in a meeting has the potential to create feelings of awkwardness or embarrassment for users. Keltner and Buswell [44] demonstrated that social embarrassment is a complex emotion. Several factors, such as loss of control and failure of privacy regulation, can make the early adoption of new user interfaces difficult [19, 68]. Rico and Brewster also aimed a part of their work [8] at exploring social acceptability, dividing it into two viewpoints: how individuals feel while interacting; and how others perceive the user interaction. Montero et al. [60] adopted this concept and refined these two viewpoints into *"User's Social Acceptance"* and *"Spectator's Social Acceptance"*, which other researchers, such as Ahlstrom et al. [1], incorporated into their studies.

This work focuses on an intraoral interface whereby interactions mimic an edible object, which is an acceptable behavior. When resting and not interacting, we envisage it to be invisible to others as users would be able to hide the interface at different places inside the mouth cavity. We conducted several studies to examine the acceptability of such an interface in terms of user perspective and spectator perspective.

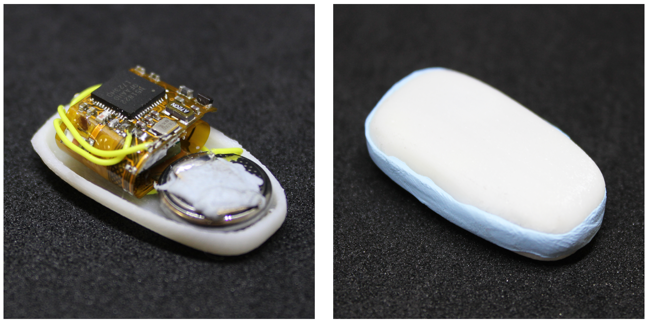

Figure 2: ChewIt prototype – basic hardware is integrated with flexible custom-made PCB, placed inside the 3D-printed casing, developed from a polylactic acid filament.

3 CHEWIT

ChewIt is a novel intraoral interface, similar to an edible object, offering new ways to perform hands-free interactions. ChewIt can be easily inserted and removed whenever the user pleases, as it is not attached to the mouth. ChewIt's design enables the user to utilize several tongue and bite gestures that mimic the behavior of interacting with an edible object so that it does not draw increased attention of others. Furthermore, the device can be hidden in the mouth when not interacting, making it invisible to spectators. Based on the high level of dexterity and proprioceptive abilities of the tongue, once being familiar with the enabled input gestures, ChewIt can favour reflexive interaction [56] potentially decreasing task load in multitasking scenarios.

Key Features

ChewIt's form factor and positioning inside the mouth provide a variety of unique features. In summary, the device:

- can be easily hidden in the mouth *(see Figure 1b)* and thus remains invisible when not interacting;
- is ready to interact as soon as the user takes it from its location *(see Figure 1c)*;
- can be discreetly interacted with natural tongue gestures, as the device can be easily moved around, such as changing orientation, flipping, etc;
- does not obstruct speech when not in use. In some instances, users were able to drink and eat while holding the interface in the mouth;
- does not require specific user adjustment or calibration as it follows a straightforward implementation;
- enables hands-free and eyes-free interaction in a mobile context, offering an additional interaction channel or being an assistive device for users with impairments.

Implementation

Form: We used a polylactic acid filament (PLA) [23] to fabricate the casing according to the shape we determined based on our studies *(see Figure 2)*. The electronics were populated into a flexible PCB to enable a better fit into the 3D-printed casing. The dimensions of the final device are $30 \times 16 \times 7$ mm, with a weight of approximately 3.92g. As the components of our prototype are not 100% bio-compatible, we covered the device with a thin latex layer. Additionally, we attached a cotton string to the device to prevent the user from swallowing it, although this use case is highly unlikely.

Hardware: The technology behind the ChewIt prototype is based on an Inertial Measurement Unit (IMU). We used an MPU-9250 [6], a 9-axis motion tracking device that combines a 3-axis gyroscope, a 3-axis accelerometer, a 3-axis magnetometer, and a Digital Motion Processor (DMP), which are all integrated into a small $3 \times 3 \times 1$ mm IC. Using this IMU, we determine the orientation and movements of the device. In addition, we also placed a button inside the device, which can be triggered by a biting gesture. A 2.4GHz low-power SoC (nRF51822 [51]), embedding a microcontroller and Bluetooth transceiver, handles the data stream. The IMU and the microcontroller communicate via I2C protocol. The maximum bandwidth was 1.9KB/s. The button uses a simple GPIO interface. Currently, the average energy consumption of the device is approximately 10.6μA when in idle mode and 10mA when fully operating. The hardware is powered by a CR1220 coin-cell battery, which enables it to run for approximately three hours. To save power, the prototype is resting in a low-power mode waiting for an activation, such as bite.

Gesture Recognizer: To prove technical feasibility and to gain some initial user impressions, we implemented a gesture recognizer driving a machine learning approach by using a conservative feature engineering.

Data Gathering: First, we recorded raw data from the accelerometer, gyroscope, and the button. We did not utilize the IMU's magnetometer, since ChewIt should be invariant to the absolute orientation of the user. Although the IMU is capable of providing high sample rates, we sampled the data at 100Hz in order to reduce power consumption and possibly avoid jitter. As each gesture can be executed in less than 2.5 seconds, we selected a window size of 256 samples. For our training data set, we recorded a single window containing a single gesture. We selected 9 gestures + 1 default gesture, in which the user was continuing his daily routine. We did not include the "Swipe"-gesture, as it is based on the surface of the device. We recorded 42-90 repetitions of each gesture (class). These classes were recorded in static and dynamic conditions such as directing the head left, right, up, and down while sitting and walking. We recorded our test set on the next two days – finally containing 31 repetitions for each class. This way, our collected test data set is spatially and temporally separated from the training set. We decided to do this to avoid strong over-fitting effects and thus to increase the stability of the model generated by the classifier.

Table 1: Classifier Performances (Recall Rate).

Classifier	SVM	RF	BN	IbK	DT
Recall	96.77%	97.1%	95.48%	89.35%	86.13%

Feature Engineering: Because our gathered input data is rather low-dimensional, as the recorded repetitions are little, we have chosen a conservative feature engineering instead of utilizing a neural network approach. Therefore, for each window, we calculated 49 different features per input trajectory, as we also combined axes from the accelerometer and gyroscope. Thus, each class was described with 402 computed features. The attribute selection of a J48 DT implementation determined these attributes as the most meaningful ones:

meanCrossings(Button), minElement(Gx), rotationIndexFeature(Gx), firstQuartile(Gx), meanCrossingsAll, activityUnitAll, meanCrossings(Az), maxElement(Ay), maxElement(Gz), minElement(Gx), spectralLowHighBandQuotient(Ax), rotationIndexFeature(Ay), spectralEnergy (Gy), interQuartileRange(Az), frequencyDifferenceOfSecondAndThirdQuartile(Ax), rotationIndexFeature(Ay).

Classifier Selection: To evaluate which classifier would provide high performance, we undertook an empirical approach comparing a Support Vector Machine (SVM), Random Forest (RF), Bayes Net (BN), K-nearest neighbours classifier (IBk), and a computational inexpensive C4.5 Decision Tree (DT) by using a leave-$k_{instances}$-out method. Thereby, each instance represents a single repetition of an entire gesture. In total, the training set incorporated 617 instances, as the test set had a size of 310 instances. We built several models based on our training data set and tested the performance with our test data set. The results are displayed in *Table 1*. Comparing recall rates, a one-way ANOVA for correlated samples ($F_{4,36}$ = 3.93, p<.01) revealed a statistical main effect. A Tukey's HSD revealed that both, the SVM (M = 96.77%; SD = 6.86%) and the RF (M = 97.1%; SD = 3.86%), were performing significantly better than the DT (M = 86.13%; SD = 18%). When unwilling to compromise on accuracy, the RF may be the best choice here. However, when aiming to implement a computational inexpensive gesture recognizer, the DT seems to provide reasonable results.

Performance Level: To determine where most confusions occurred, we included the confusion matrix of the DT in *Figure 3*. The visualization indicates that bite gestures ("Incisor Bite", "Molar Bite", and "Peripheral Bite") resulted in greater confusions compared to other tongue gestures. This is due to the limitations of our initial prototype, which only incorporated a single button. However, with the current prototype, we can achieve reasonable accuracy above 95% with the top five gestures (+ default class: "No Gesture"). Considering this reduced set, we also implemented a real-time gesture recognizer using a DT and utilizing a sliding window approach, while shifting the window every 16 samples.

Classified as >	A	B	C	D	E	F	G	H	I	J
A. Location: Bottom to Top	96.8	0	0	0	0	3.2	0	0	0	0
B. No Gesture	0	100	0	0	0	0	0	0	0	0
C. Translation: Front-Back	0	6.5	83.9	0	0	6.5	0	0	0	3.1
D. Incisor Bite	0	0	0	83.9	0	0	16.1	0	0	0
E. Translation: Left-Right	0	0	3.2	0	93.6	0	0	0	0	3.2
F. Location: Middle-Side	0	0	0	0	0	100	0	0	0	0
G. Molar Bite	0	0	0	22.6	0	0	71	6.4	0	0
H. Peripheral Bite	0	0	0	0	0	0	58.1	41.9	0	0
I. Rolling	0	0	0	0	0	0	0	3.2	96.8	0
J. Location: Side to Side	0	0	3.2	0	0	3.2	0	0	0	93.6

Figure 3: Confusion matrix for the 9 gestures (+ 1 default class: "No Gesture") for a C4.5 Decision Tree. The numbers are in percentages. The overall F1 Score is 0.861.

4 PERSPECTIVES & GENERAL FEASIBILITY

At the beginning of this research, we sought to understand the acceptance and general feasibility of an intraoral interface. Therefore, we conducted 3 user studies to investigate the spectator's perspective when an object is placed in the mouth (study 1), the user's perceived obstruction when pursuing daily tasks with an object in the mouth (study 2), and understanding user habits and limitations when using common intraoral objects, such as chewing gums (study 3).

Study 1: The Spectator's Perspective

We investigated the discreetness of an intraoral object, placed inside the mouth, from a spectator point of view.

Participants & Procedure: We used 2 different object sizes, small (25 × 15 × 7 mm, $1Kmm^3$) and large (30 × 18 × 7 mm, $3Kmm^3$), and recorded 2 users with the large object, the small object, and no object in the mouth. These recordings were taken for talking, smiling, and rotating the head from left to right. In summary, we created the following set of images/animations:

(1) **Talking**: 3 videos (2 facial side views of 2 users, 2 facial front views of 2 users)
(2) **Smiling**: 3 still images (2 facial side views of 2 users, 2 facial front views of 2 users)
(3) **Rotating Head**: 3 videos (1 view each from 2 users)

These viewing conditions were distributed as an online survey. Participants were instructed to point the images where they could spot the devices. In case of doubt, they were asked to not make a selection. The survey was completed by 42 participants, from which 14 were female, with an age range of 20 to 55 years.

Response	**1. Talking**	**2. Smiling**	**3. Rotating Head**
Large object	42%	29.6%	37.6%
Small object	20.4%	22%	23.7%
No object	14.9%	22%	17.2%
Unsure	22.7%	26.4%	21.5%
Correct	62.4%	51.6%	61.3%
Incorrect	37.6%	48.4%	38.7%

Table 2: Detection of the presence of an object in the mouth by a spectator.

Results

Confidence: Although we took pictures under different light conditions, an ANOVA did not evidence the light condition to have a main effect on the participants' confidence level for Condition 1 ($F_{3,154}$ = 0.155, p>.05) and Condition 2 ($F_{3,154}$ = 0.214, p>.05). We also ran a t-test for Condition 3, which also did not show any statistical difference ($T(76)$ = 0.507, p>.05). For the majority of answers, the participants were not fully confident in identifying the image/animation which depicted an object in the mouth (M=63.66%; SD=1.75). In only M=3.15% (SD=0.56) of all cases, participants stated to be confident in identifying the object.

Accuracy: When drawing attention to the fact that there was a hidden device *(see Table 2)*, the participants could correctly identify the larger size in M=36.4% (SD=6.3%) of all the cases and the smaller size to a percentage of M=22.05% (SD=1.61%). Answers that were mistaken are M=18.05% (SD=3.64%). In M=23.5% (SD=2.53%) of all cases, the spectator could not detect anything.

In conclusion, we found that spectators hardly noticed a chewing interface, when no interaction occurred and when the interface merely rested inside the buccal cavity. As two correct answers were included among the three images, there was a higher possibility that participants would guess with greater accuracy. However, the data appears almost normally distributed. Incorrect answers were slightly higher than 33%, as some participants did not spot any device in their responses. In terms of confidence, we can also confirm that most participants did not feel fully confident while trying to spot the devices, once again evidencing that the device is hardly noticeable when not interacting.

Study 2: User's Perspective

In this study, our goal was to determine the level of obstruction a user may perceive when carrying an intraoral object.

Participants & Procedure: We recruited 10 participants (3 females, 7 males) and provided them with a rectangular object (10 × 20 × 5 mm) produced from a Class IIa long-term bio-compatible resin [24]. We asked them to hold the object in their mouth between the inner cheek and the teeth (Molar or Premolar). Participants were required to perform daily office activities for 60 minutes, including writing and typing, etc, during this time we had conversations with them for 30 minutes and observed their behaviour throughout. After the experiment, we asked participants to rate the perceived obstruction on a 5-point Likert scale (1: not obstructing at all, 5: absolutely obstructing).

Results

Low Self-Perceived Obstruction: On average, participants did not feel disturbed with an object being placed in the mouth (M = 2.1/5; SD = 0.57). P6: *"I almost forgot having the device inside the mouth before you started talking to me."* Two participants changed the location of the object because they were irritated by the constant pressure against the mouth tissue. All participants were still capable of clearly articulating themselves without noticeable difference. Some participants were even able to drink a beverage and consume a snack with the object in their mouth.

Study 3: Understanding Habits and Limitations

In this study we aimed to investigate user habits when chewing a piece of gum.

Participants & Procedure: We recruited 14 participants (5 females, 9 males) and provided them with a piece of regular chewing gum. The task was to chew it until their jaws experienced fatigue. Once they finished chewing, we asked participants to hide the gum in their mouth. Additionally, we asked them to point out the area in which they were holding the gum in their mouth (*see Figure 1b*: Molar <Blue>, Premolar <Yellow>, Cuspid <Red>, Incisor <Green>).

Results

Chewing Time: The minimum chewing time until a participant decided to stop chewing was 17.35 minutes (M = 41.86; SD = 18.69). Two users chew the gum for more than one hour, indicating not being bothered to continue.

Holding Location: All but one participant used the Molar or Premolar teeth for chewing. All participants either held the chewing gum between those teeth or in the inner cheek, as the inner cheek was the preferred location.

5 DESIGN RATIONALE

The design of our prototype was informed by four studies, in which we focused on different aspects such as *Dimensions*, *Form Factor* and *Gesture Feasibility*.

Study 4: Implications on Dimension

In this study, we sought to evaluate possible dimensions that would be most comfortable for the user and questioned whether size affects basic physiological activities.

Participants & Procedure: We recruited 12 participants (2 females, 10 males), asking them to hold objects of several sizes between the inner cheek and teeth. The objects were

3D printed, using the same bio-compatible resin from the previous study. We started with a rectangular-shaped object ($10 \times 20 \times 5$ mm) and incrementally expanded its size in one dimension. First, we increased the width by increments of 5mm. Participants had to rate the clarity of speech with a 5-point Likert scale and they chose the size that they were most comfortable with. Second, the chosen object was then expanded in length by an increment of 5mm. Participants had to rate the impact of the object on their facial expressions using a 5-point Likert scale and chose the size that they are most comfortable with. Lastly, the thickness was expanded by an increment of 5mm and participants were asked to rate "puffiness" of the face with a 5-point Likert scale and chose the one they felt was most comfortable *(see Figure 4)*.

Results

Size: All participants found a width of 10mm to be comfortable. Only 6 out of 13 participants found the subsequent size of 15mm to be comfortable. A length of 20mm was reported to be comfortable by all participants. Only 6 out of 13 participants found the subsequent size of 25mm to be comfortable. Thickness of 5mm was found to be comfortable to all participants. Only 1 participant reported the next size of 10mm to be comfortable.

Clarity of Speech: Statistical differences for (1) clarity of speech (Q = 23.52, p<.05, DF = 36) are confirmed by a Friedman test (k=3). A post-hoc analysis using Nemenyi's procedure (k=3) two-tailed test found a significant difference (p<.05) between size A (M= 4.5; SD= 0.54) and size B (M= 3.62; SD= 0.62) and between size A and size C (M= 3.04; SD= 0.78). There was no statistical difference between B and C.

Impact of Facial Expressions: A Friedman test indicated a statistical difference of (2) facial expressiveness (Q = 37.74, p<.05, DF = 36). A post-hoc analysis using Nemenyi's procedure (k=3) two-tailed test found a significant difference (p<.05) between size A (M= 4.35; SD= 0.72) and size E (M= 1.808; SD= 0.88). There was no statistical difference between D (M= 3.04; SD= 0.75) and E.

Impact of Facial 'Puffiness': Wilcoxon's test (k=3) indicated that self-perception of the "puffiness" of the face (V = 88.5, p<.05) was significantly different between size A (M= 4; SD= 0.89) and size F (M= 2.15; SD= 0.8).

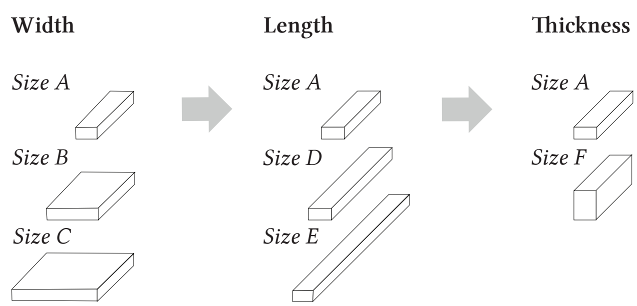

Figure 4: We expanded the object in one dimension in the following order of width, length, and thickness.

Based on the results, we found the size of 10mm (width), 20mm (length), and 5mm (thickness) to be acceptable.

Study 5: Implications of Shape

In this study, we investigate how users perceive different geometrical shapes in terms of comfort, orientation recognition, and the ease of maneuvering it within the mouth.

Participants & Procedure: We recruited 12 participants (3 females, 9 males) to interact with 4 different shapes. These were (1) Asymmetrical Spherical Wedge (2) Spherical Cut, (3) Rectangular Prism, and (4) Triangular Prism *(see Figure 5d)*. Building from the results of the previous study, we selected the dimensions $10 \times 20 \times 5$ mm, All of them had a volume of $1Kmm^3$ and similar proportions.

We asked participants to orient and rotate the object along pitch-, roll-, yaw-axis *(see Figure 1d)* and rate the comfort, understandability of the object's orientation, and ease of maneuverability of it on a 5-point Likert scale (1:worst, 5:best).

Results

Orientation: Friedman's test (k=4), indicated a statistical difference (Q = 32.09, p<.05, DF = 44) between the shapes in terms of orientation 5.a. A post-hoc analysis using Nemenyi's procedure (k=3) two-tailed test found significant difference (p<.05) between Asymmetrical Spherical Wedge (M= 4.5; SD= 0.74) and Rectangular Prism (M= 2.53; SD= 0.65), between Spherical Cut (M= 4.5; SD= 0.74) and Rectangular Prism and between Triangular Prism (M= 3.7; SD= 1.22) and Rectangular Prism. There was no statistical difference (p>.05) between Triangular Prism and Spherical Cut.

Maneuverability: Friedman's test (k=4), indicated a statistical difference (Q = 29.17, p<.05, DF = 44) between the shapes in terms of maneuverability 5.b. A post-hoc analysis using Nemenyi's procedure (k=3) two-tailed test found significant difference (p<.05) between Rectangular Prism (M= 3.1; SD= 0.85) and Asymmetrical Spherical Wedge (M= 1.63; SD= 0.87) and between Rectangular Prism and Triangular Prism (M= 2.3; SD= 0.89). There was no difference (p>.05) between Triangular Prism and Spherical Cut (M= 2.9; SD= 1.2).

Comfort: Friedman's test (k=4), indicated a statistical difference (Q = 12.9, p<.05, DF = 44) between the shapes in terms of comfort. A post-hoc analysis using Nemenyi's procedure (k=3) two-tailed test found significant difference (p<.05) between Asymmetrical Spherical Wedge (M= 3.17; SD= 1.03) and Rectangular Prism (M= 1.75; SD= 0.965) and between Spherical Cut (M= 3.17; SD= 0.93) and Rectangular Prism. There was no statistical difference (p>.05) between Triangular Prism (M= 1.92; SD= 0.79) and Spherical Cut. Participants commented that flat surfaces are more comfortable

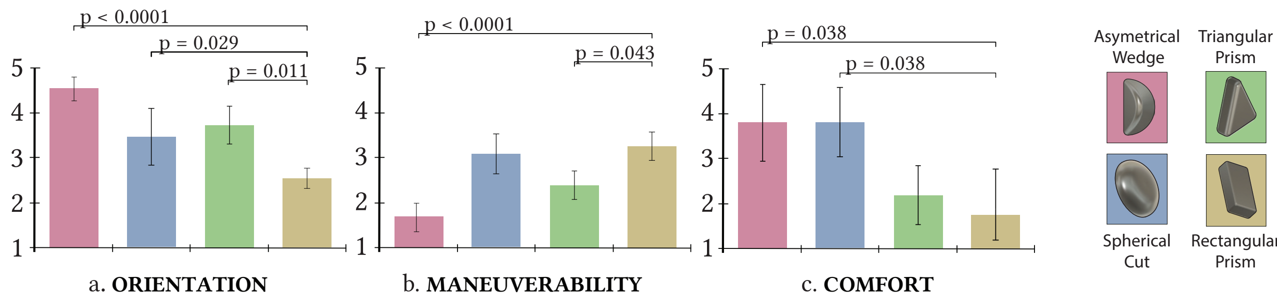

Figure 5: Four different 3D-printed objects were used to study the implication of shape. Average scores were recorded for the understandability of orientation, ease of maneuvering and comfort (1:worst, 5: best)

than round surfaces when placed against the teeth. However, round surfaces were reportedly more comfortable against the cheek compared to flat surfaces. This occurs because of the anatomical features of the mouth. Users frequently reported that when placing a round surface against a non-flexible tissue, such as the teeth, the shape applies pressure onto a small area, which does not allow the object to be stable nor comfortable. However, as the inner cheek is a flexible tissue, having a round shape against it enables a better grip and increases comfort. Therefore, we avoided corners and sharp edges, as they are uncomfortable and may even cut the soft mouth tissue.

Holding Location: The Molar area is preferred (Asymmetrical Spherical Wedge: All participants; Spherical Cut: 11 out of 12 participants; Triangular Prism: 11 out f 12 participants; Rectangle: 9 out of 12 participants), and as such the device will be designed to fit inside the Molar cavity *(see Figure 1b)*.

Shape of ChewIt: We followed a systematic process to generate a reasonable shape for ChewIt. ChewIt's shape underwent various transformations. Based on the rectangle dimensions extracted from the previous study, we removed sharp corners *(see Figure 6b)*. This was transformed to an asymmetric shape with a uniform weight distribution. These features are important to understand orientation and maneuverability *(see Figure 6c)*. ChewIt also transformed to have a flat surface on one side and a rounded surface on the opposite, allowing it to be held with the inner cheek and to sit comfortably in the teeth *(see Figure 6d)*.

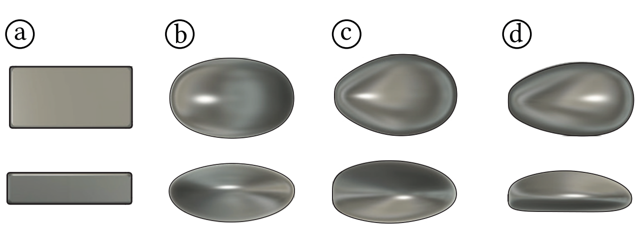

Figure 6: The shape was derived based on previous findings. (Top row: top view; bottom row: side view)

Study 6: Volume Factor

In this study, we evaluate the impact of different volume proportions in terms of comfort and self-perceived discreetness.

Participants & Procedure: We recruited 13 participants (4 females, 9 males), who were given six objects with different volumes: (A) $0.25Kmm^3$, (B) $0.5Kmm^3$, (C) $0.75Kmm^3$, (D) $1Kmm^3$, (E) $2Kmm^3$, and (F) $3Kmm^3$. These were administered one at a time, and participants were asked to orient the object in different ways inside the mouth. The order of the objects was randomized.

Participants were asked to rate the maneuverability when they were orienting the device using a 5-point Likert scale (1: very easy, 5: very difficult). Participants were also asked to hide the object at two locations *(see Figure 1b)*: Location 2 (at the Bottom, blue) and Location 1 (at the Top, black). After testing each location, participants were asked to indicate their preference for each location based on self-perceived comfort and discreetness.

Results

Shape: To analyze the differences in maneuverability, we ran a one-way ANOVA, which confirmed a significant main effect ($F_{5,72}$ = 3.594, p<.05) between sizes *(see Figure 7)*. A post-hoc analysis using Tukey's HSD test revealed statistical differences between Size D (M=4.58; SD=0.73) and Size A (M=3.3; SD=1.39) and between Size E (M=4.52; SD=0.64) and

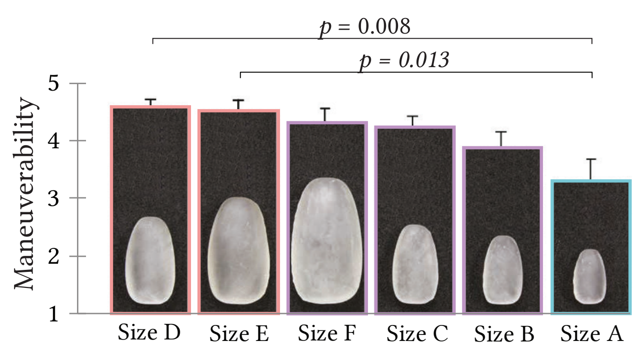

Figure 7: Impact of volume on maneuverability (1: very easy, 5: very difficult) for 6 volumes: A $0.25Kmm^3$, B: $0.5Kmm^3$, C: $0.75Kmm^3$, D: $1Kmm^3$, E: $2Kmm^3$ and F: $3Kmm^3$

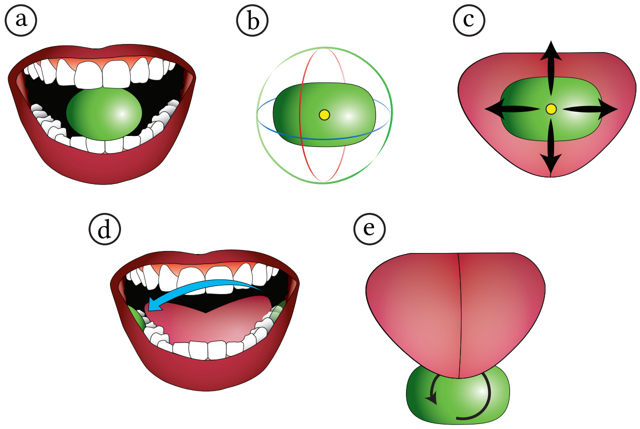

Figure 8: Gestures Types: a) Bites. b) Rotations. c) Tongue Movement. d) Location Changes. e) Tongue Drawing.

Size A. Size A was the size with the lowest mean score. There were no other statistical differences (p>.05). Size D and Size E also had the higher mean score. Therefore, we chose a size between Size D and E as a reasonable size.

In conclusion, we found smaller shapes to be easier to maneuver but excessively small ones were difficult to orient. However, the largest sizes were found easy to orient but could become cumbersome to move.

Holding Location: We did not find a preferred location *(see Figure 1b)* in terms of comfort, as 8 out of 13 participants chose Location 1 (at the Top, Black) and 5 out of 13 participants chose Location 2 (at the Bottom, Blue). However, we observed that all participants, in terms of discreetness, chose Location 2 as the most preferable position for hiding the object. As we prioritize the discreetness of the interface, the devices will be optimized to fit best into Location 2.

Study 7: Defining Gestures

Finally, we explore potential gestures that users could use to interact with an intraoral interface.

Participants & Procedure: We recruited 11 participants (3 females, 8 males) to study 14 gestures. The gestures are divided into 5 main groups *(see Table 3)*. *(a) Bites:* performed by pressing the object with the teeth from opposite sides. We study the bites performed on the periphery of the object's surface (Peripheral Bite) and the bites performed on the center of the surface, using the Incisors and the Molars teeth *(see Figure 8a)*; *(b) Rotations:* performed on Roll, Pitch, and Yaw axis *(see Figure 8b)*; *(c) Tongue Movements:* performed by placing the object on the top of the tongue and moving it from the left to the right or from the front to the back *(see Figure 8c)*; *(d) Location Changes:* performed by moving the object from one place of the mouth to another *(Figure 8d)*; *(e) Tongue Drawing:* performed by using the tip of the tongue to draw either Swipes or Complex Drawings, such as circles, triangles, or squares *(see Figure 8e)*.

To help the participant understand the gestures, the experimenter demonstrated them with a 3D-printed replica of a mouth. After performing each gesture, the participants were asked to rate them based on (1) Ease of Use, (2) Natural Look, (3) Comfort, (4) Unobtrusiveness. The ratings were completed using a 5-point Likert scale (1:worst, 5:best). The order in which the gestures were performed in were randomized. Also, to judge the 'natural look', we placed a mirror in front of the participant.

Results

Gesture Feasibility: Our evaluation revealed that gestures have individual strengths and weaknesses *(see Figure 9)*, depending on the observed parameter. While some gestures, such as *Complex Drawings* and *Tongue: Middle to Front* are hardly noticeable, they are difficult to perform. Across all the ratings, we found that the gestures *Pitching* as well as *Location Middle to Front* are less preferred. A one-way ANOVA showed a statistical main effect across all ratings: Ease of Use ($F_{13,181}$ = 7.84, p<.05), Natural Look ($F_{13,181}$ = 4.7, p<.05), Comfort ($F_{13,181}$ = 6.22, p<.05) and Unobtrusiveness ($F_{13,181}$ = 4.38, p<.05). The post-hoc analysis is accomplished using a Tukey's HSD to determine detailed significances.

In order to discriminate a subset for each parameter, we followed two criteria: 1) Gestures need to have a *strong* interpretation (i.e., mean Likert ratings in the top Quartile), and 2) The chosen gesture(s) need to be statistically different from as many *non-strong* gestures as possible.

Comfort: The subset deduced for this parameter involves two gestures: *Rolling* (M= 4.54; SD= 0.52) and *Molar Bite*(M= 4.46; SD= 0.66).

Ease of Use: The subset deduced for this parameter involves two gestures: *Molar Bite* (M= 4.53; SD= 0.52) and *Rolling* (M= 4.46; SD= 0.66).

Bites *(Figure 8a)*	Incisor Bite
	Molar Bite
	Peripheral Bite
Rotations *(Figure 8b)*	Pitching
	Rolling
	Yawing
Tongue Movement *(Figure 8c)*	Front-Back
	Left-Right
Location Change *(Figure 8d)*	Side to Side
	Bottom to Top
	Middle to Side
	Middle to Front
Tongue Drawing *(Figure 8e)*	Swipes
	Complex: Circle, Triangle, Square

Table 3: Fourteen gestures have been defined. Peripheral Bite is performed on the object's peripheral surface. Incisor and Molar bites are performed at the center of the device using the Incisors or the Molar. Rotations around the axis are shown in *Figure 1d.*

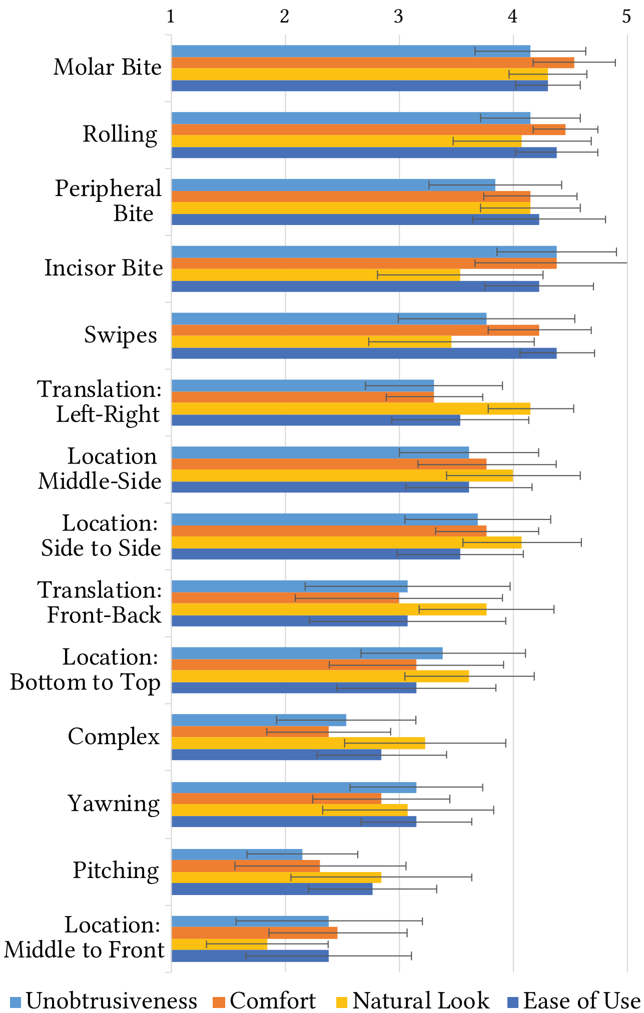

Figure 9: Average User rating for each gestures in terms of Ease of Use, Natural Look, Comfort, and Unobtrusiveness.

Natural Look: . The subset deduced for this parameter involves ten gestures: *Molar Bite* (*M*= 4.31; *SD*= 1.33) , *Translation: Left-Right* (*M*= 4.15; *SD*= 0.69), *Peripheral Bite* (*M*= 4.15; *SD*= 0.8), *Location: Side to Side* (*M*= 4.08; *SD*= 0.95), *Rolling* (*M*= 4.08; *SD*= 1.12), *Location: Middle to Side* (*M*= 4; *SD*= 1,08), *Translation: Front-Back* (*M*= 3.77; *SD*= 1.09), *Location: Bottom to Top* (*M*= 3.62; *SD*= 1.04), *Incisor Bite* (*M*= 3.54; *SD*= 1.33) and *Swipes* (*M*= 3.46; *SD*= 1.33).

Unobtrusiveness: The subset deduced for this parameter involves three gestures: *Incisor Bite* (*M*= 4.38; *SD*= 0.96), *Molar Bite* (*M*= 4.15; *SD*= 0.9) and *Rolling* (*M*= 4.15; *SD*= 0.8).

Based on the users' ratings on 4 parameters (Unobtrusiveness, Comfort, Natural Look and Ease of Use) we identified two gestures that stood out from the rest: *Rolling* and *Molar Bite*. However, in case the scenario requires a larger input bandwidth, the range of gestures can increase up to ten without affecting the discreetness of the interactions.

6 CONTRIBUTION AND BENEFITS

The main contribution of this paper is the idea of an intraoral interface, which is similar to an interactive edible object. Such an interface will not only benefit impaired people, but also users in daily hands-busy situations, particularly when performing high precision tasks that require both hands [13]. Furthermore, we contribute with our design decisions and findings on *Interaction time, Holding Location, Shape Considerations, Comfort on Shape, Dimensions and Volume Considerations, and Gesture Feasibility.*

Minimum Interaction Time: Our studies revealed that participants felt comfortable with holding a small object in their mouth for at least 15 minutes. This was assessed while the distraction continued with their daily tasks.

Two Holding Locations: We identified two locations *(see Figure 1b)* in which the users are able to hide an introal interface. The first location (at the Top, Black) is the buccal shelf on the *Maxilla*, next to the *Zygomatic Bone*, partially under the *Masseter Muscle*, and the second is at the Body of the Lower Jaw Bone, under the Molar area (at the Bottom, Blue). With the first location, the device seems to be less visible to others.

Two Basic Shape Considerations: We investigated 4 types of shapes, which are an Asymmetrical Spherical Wedge, a spherical cut, a rectangular prism, and a triangular prism. We developed 2 conclusions from such findings: Among those shapes, we found asymmetry to be an important factor in understanding the orientation of the device; a flat surface on one side and a rounded surface on the opposite maximizes the grip and the comfort. In future, we aim to specifically explore into texture perception and weight distribution.

Comfort on Shape: While performing the studies, we discovered that users mostly preferred rounded corners. Sharp corners should be avoided at all cost, as there is a high chance of cutting the soft tissues inside the mouth. This fact is reflected by the comments from users, suggesting that pressure exerted by the small corners were irritating and annoying.

Dimensions and Volume Considerations: The dimensions of an object placed inside the buccal cavity can affect the clarity of speech, facial expression, and the self-perception of the face. Smaller sizes seem to be easier to maneuver inside the mouth. Where the size is excessively small, users will find it difficult to orient. Likewise, larger sizes are easy to orient but cumbersome to maneuver.

Self-perceived and Spectator-perceived discreetness: Users suffer from a subjective effect when wearing different devices, regardless of the size. This could be due to the sensation of having something inside the mouth. However, this was hardly noticeable by spectators in the user's vicinity, even with the largest object size.

Gesture Feasibility: We propose 2 gestures that stand out across all the studied parameters: *Rolling* and *Molar Bite*. However, there are 8 more gestures that can be used if a particular application needs larger input bandwidth, without compromising the discreetness.

Multitasking. ChewIt allows for multitasking, including gestures with low levels of obstruction *(see Figure 9)*, which will enable users to perform basic tasks, such as speaking while wearing the interface. We observed that some users were even able to drink and eat while having ChewIt in the mouth. However, we do not recommend this, as there is a high risk of swallowing it. In future, we aim to specifically explore how users experience drinking, eating, and other physiological activities while wearing the device, and also to find implementation alternatives that could benefit the user in case the device is swallowed.

7 LIMITATIONS

Although ChewIt enables new opportunities for future HCI, it inevitably has certain limitations, as with every other technology.

Hygienic Aspects: Concerns regarding hygiene and sterilization are evident when placing devices inside the mouth or spitting them out. Sharing ChewIt may therefore be inappropriate or unacceptable by users.

Safety Concerns: A major concern in our studies was to avoid any type of bacterial infection risk. Therefore, we used a bio-compatible resin that can be sterilized with alcohol after every use and can be 3D printed by the FormLabs2 Printer. When deploying ChewIt as a product, a crucial factor is the type of battery used. Silver oxide batteries are a possible option. Although they are not biocompatible, silver oxide batteries are used in colonoscopy cameras [79, 80] and are still safer than Lithium batteries. Also, using electronic components which are absolutely biocompatible proves challenging.

Material Properties: While the current prototype is based on a rigid material, it is desirable to use a flexible material. This material must withstand several conditions, including being biocompatible, resistant to bacteria, and stand high forces of extensive biting. We recommend the usage of a bio-compatible silicon compound.

Prototype: The current prototype has an 86.14% of overall accuracy within all 10 possible gestures. We plan to increase the accuracy by implementing existing solutions into the next prototype iterations. These solutions take into account the orientation of the object and the inertia when walking by including: 1) a secondary IMU [65], 2) taking into account existing inertia [88] and the pendulum-like behaviour when walking [89], 3) the orientation of the device [78], and 4) a pressure matrix that detects bites on different regions within the surface of ChewIt. However, real-world scenarios do not demand such a high bandwidth of gestures for controlling conventional interfaces. We recommend a subset of 2 gestures: *Rolling* and *Molar Bite* for general purpose applications, such as controlling a music interface, controlling a wheelchair, or navigating through menus while engaging in another activity. As mentioned before, the accuracy of the current prototype for a subset of 2 gestures is 94.98%.

Social Acceptability : Using a discreet intraoral interface may be a novel way to interact hands-free. We evaluated social acceptance based on whether a spectator could detect that a user is holding ChewIt, as well as if a user's perceived obstruction. However, social acceptability is a complex emotion [44] that depends factors such as context, individual preferences, and culture. While our initial evaluation indicates that ChewIt offers a variety of discreet gestures, their social acceptance remains untested.

8 CONCLUSION AND FUTURE WORK

In this paper, we presented ChewIt, an intraoral interface that enables hands-free input operations. Our goal was to strike a better balance between social acceptability and expanding capabilities beyond merely providing a binary input. We studied social acceptance from a spectator's point of view, as well as self-perception, while participants used intraoral objects. We developed a prototype where design decisions were derived by a series of user studies. We view ChewIt as a novel input interface that can assist people with and without impairments.

For future work, we need to investigate ChewIt in public spaces, including among ethnic groups, to gain greater insights on the evolvement of user acceptance during long-term usage. In technical terms, one may consider using Electromagnetic Articulograph (EMA) to further determine the device's accuracy when performing input gestures or positioning tasks. Related research also indicates that non-attached intraoral devices, such as electric chewing gums [66], could be a new interaction modality infiltrating the user's body in the future.

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