SSpoon: A Shape-changing Spoon That Optimizes Bite Size for Eating Rate Regulation

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One key strategy of combating obesity is to slow down eating; however, this is difficult to achieve due to people's habitual nature. In this paper, we explored the feasibility of incorporating shape-changing interface into an eating spoon to directly intervene in undesirable eating behaviour. First, we investigated the optimal dimension (i.e., Z-depth) and ideal range of spoon transformation for different food forms that could affect bite size while maintaining usability. Those findings allowed the development of *SSpoon* prototype through a series of design explorations that are optimised for user's adoption. Then, we applied two shape-changing strategies: instant transformations based on food forms and subtle transformations based on food intake) and examined in two comparative studies involving a full course meal using Wizard-of-Oz approach. The results indicated that *SSpoon* could achieve comparable effects to a small spoon (5ml) in reducing eating rate by 13.7-16.1% and food consumption by 4.4-4.6%, while retaining similar user satisfaction as a normal eating spoon (10ml). These results demonstrate the feasibility of a shape-changing eating utensil as a promising alternative to combat the growing concern of obesity.

CCS Concepts: • **Human-centered computing → User studies**; **Usability testing**; **Laboratory experiments**; **Haptic devices**.

Additional Key Words and Phrases: Shape-changing interfaces; Eating rate; Human food interaction; Empirical study.

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105

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1 INTRODUCTION

Obesity has become one of the most significant public health concerns. If the current trends continue, it is projected to affect 1.12 billion individuals (20% of the global adult population) by 2030 [46]. This is alarming as obesity has been linked to several adverse health consequences such as diabetes mellitus, cardiovascular disease, fatty liver disease, and poor mental health, which poses a substantial economic burden for healthcare systems [66].

One promising strategy to combat overweight and obesity is to slow down the eating rate [24, 47, 74, 76, 84]. To be more specific, research has shown that the key approaches to slow eating [76] include reducing the bite size [26, 44], increasing the number of chews per mouthful [9, 26, 105], and lengthening intervals between bites [24]. These approaches can be achieved by modifying the food texture [8], such as increasing the chewiness [2] and hardness [18] so that more chews are needed to consume the food. Alternatively, real-time interventions can also be introduced to interrupt the problematic eating behaviour to nudge eaters towards healthier behavioural changes [36]. While these approaches are effective, they risk decreasing eating pleasure, which can be undesirable for many users. For instance, food form [28] modification requires substantial dietary changes [47], which can be difficult if users are not willing to change their diet. One the other hand, Using external prompters; such as visual or haptic relies on users' conscious scrutiny and self-motivation to make a change, which can affect people's eating mood and might be difficult for many users [102].

Instead of changing the food form or nudging the user, we propose that an eating spoon can not only be used as a static food serving tool but also play a more active role in human-food interaction to facilitate eating behaviour changes. Inspired by the widespread research on the shape-changing interfaces for digital displays [56, 73], handheld devices [17, 35], and food transformation [94, 101], we envision a new type of interactive possibility by introducing the shape-changing interface into the eating tool, where a shape-changing spoon can adapt its physical form dynamically and subtly to optimise the users' eating behaviour without many cognitive and behavioural costs.

To achieve this goal, multiple studies were conducted. In the first study, we investigated the impact of spoon size on both bite size and usability across three transformation dimensions (X-width, Y-length, and Z-depth) and three food forms (solid, semi-solid, and liquid). The results indicated that the Z dimension is the most effective for transformation, and there is an optimal range depending on the food form: 5-7ml for solid, 3-7ml for semi-solid, and 5-9ml for liquid. Informed by these results, we then developed *SSpoon* through a series of design exploration and used it in subsequent studies. Next, we explored the feasibility of two shape-changing strategies: instant transformations based on food form (Study 2) and subtle transformations based on cumulative food intake (Study 3). Both Studies 2 and 3 compared our dynamic *SSpoon* (from 10ml to 5ml) with the commercial static spoons (10ml or 5ml). Overall results showed that *SSpoon* could achieve comparable effects to a small spoon (5ml) in reducing eating rate by 13.7%-16.1%, and contributing to an overall reduction in food consumption by 4.4%-4.6% while retaining similar user satisfaction to a normal eating spoon (10ml). Lastly, based on explanations derived from cognitive science (e.g. reward satisfaction theory [68, 97] and confirmation bias [70]), we discussed how *SSpoon* was able to effectively satisfy the users and induce their perception of satiety.

Furthermore, our studies revealed key insights that could guide the future design of *SSpoon* to provide alternative shape-changing strategies and extend the shape-changing concept to other dietary purposes and tableware products. The results obtained from these studies could benefit practitioners and researchers who are investigating user eating behaviour or redesigning the eating experience. The contributions of this paper are thus as follows: 1) designing a shape-changing spoon artefact that dynamically changes its food-carrying volume to regulate eating rate; 2) evaluating the proposed design via two empirical studies using two shape-changing strategies in a full course meal to understand its impact on users' eating behaviour and overall experience; 3) discussing the potential of the shape-changing concept for other eating intervention designs.

2 RELATED WORK

Our work intersects with three research areas. First, we highlight how the strong association between eating rate and oral processing (i.e., eating) behaviour can be leveraged for obesity intervention. Next, we discuss how existing interventions are ineffective in reducing eating rate before revealing the untapped potential of the shape-changing interface to be incorporated in our proposed spoon design.

2.1 The Association between Eating Rate and Oral Processing Behaviour

Accumulating evidence has shown positive correlations between eating quickly and excess body weight [29, 74, 76, 84] across various age groups [47], gender [48], and cultural backgrounds (e.g., European, Asian, and American samples) [7, 84] in the both clinical and general populations. Specific parameters of oral processing behaviour, such as large bite size [5, 26, 44], fewer chews before swallowing [9, 26, 105], shorter oral exposure time[9, 26, 54]and shorter inter-bite interval[24] has been consistently identified as key contributors to rapid eating. For instance, Spiegel et al. [87]demonstrated how sandwiches consumed in smaller bite sizes (5g instead of 15g) induced a slower eating rate by 18%. In another study, Zhu and Hollis [105] instructed participants to increase their habitual chew frequency for pizza rolls by 50% and 100%, resulting in the eating rate reduction of 9.5% and 14.8% respectively. Despite the difficulty in translating experimental benefits into everyday eating scenarios, behaviour therapists have suggested moderating bite sizes as the most feasible strategy for future eating rate intervention [87]. This is because users are more likely to eat food that has been cut into smaller size, rather than prolonging the pauses between bites by intentionally putting the food or utensils down, which could interrupt their natural eating experience. Inspired by these findings, we aim to investigate how moderating the bite size can be facilitated more naturally to maximise user adoption.

2.2 Existing Eating Rate Interventions to Tackle Obesity

Rapid eating is difficult to change once established [59]. Previous attempts at reducing eating rate can be broadly categorised into two groups: (1) Food modification to encourage more chewing or smaller bite sizes [8, 12]; (2) External systems that provide visual or haptic feedback during the meal [19, 39, 51]. External food texture manipulation such as increasing the hardness may adversely impact sensory perception and palatability, ultimately resulting in a lower acceptance and habit sustainability [9, 27]. On the other hand, external devices that modulate eating experience through multisensory cues can be a less disruptive way to consider. For instance, *10s fork* [36, 37] is a smart fork that vibrates whenever an interval between two mouthfuls of less than 10s is detected. Another example is *Eating2Pic* [69] which is a painting system that nudges against rapid eating behaviour by poorly colouring landscape pictures. However, one limitation of these devices is that they strongly rely on individual motivation and the ability to self-regulate [102]. Furthermore, the "boredom effect" can be quite significant as people cease to pay attention to external prompters over time [32].

The most relevant to our study originates from Zhang et al. [102], who demonstrated the concept of developing a pneumatic handle prototype to interfere with rapid eating behaviour. They increased or decreased the rigidity of the utensil handle by inflating or deflating air. While they postulated that their proposed design could be used to facilitate or interfere with eating rate, the user acceptability and system efficacy were underexplored. In light of this study, we propose an in-depth investigation of a spoon head as an alternative intervention design. In theory, the head component targets a more direct area related to the oral processing behaviour - large bite size. We hypothesised that, instead of modifying the spoon handle rigidity, our proposed method of decreasing spoon head volume to limit bite size - could be a less intrusive yet effective eating intervention without compromising the eating experience.

2.3 Shape-changing Interface Related to Volume Changes

Shape-changing interfaces have become an emerging field in Tangible User Interfaces(TUIs). Shape parameters like orientation, form, and texture have been manipulated to trigger dynamic interactions [90]. Among those, volume change was catalogued as one of the transformation types of deformation widely used in shape-changing interfaces [79]. For example, Kim et al. [49] introduced *Inflatable Mouse*, which inflates/deflates the traditional mouse to make it more portable and usable. *Volflex* [43] is a volumetric surface display that could dynamically deform from a flat, circular display to a convex, hemispherical display in response to the user's task. Kinch et al. [50] introduced *coMotion*, a shape-changing bench that facilitates social situations by sparking conversations between strangers in the wild. Although the aforementioned examples cover various applications, including wearable devices [6, 33, 33, 92], interactive buttons and controls [89, 100], dynamic furniture [93, 103], digital display devices [73], and accessibility [11, 55], the application of shape-changing interfaces into a more intimate context, such as human-food interaction is yet underexplored [94]. Inspired by these previous efforts, we extend the line of research by developing a shape-changing interface for the eating context and investigating its impact on eating rate, food intake, appetite, and user acceptability.

3 STUDY 1: IDENTIFY THE OPTIMAL DIMENSION AND RANGE OF SPOON TRANSFORMATION

To effectively design a shape-changing spoon, we need to first understand which design factors of the spoon are acceptable and feasible for the transformation. Specifically, in this study, we aim to investigate how spoon sizes affect bite size and usability across three dimensions (i.e., X, Y, and Z) and three food forms (i.e., solid, semi-solid, and liquid); hence, the following two main research questions are investigated:

RQ1: How does spoon size affect bite size and usability across different dimensions of transformation? Which dimension is optimal in minimising bite size and maximising usability?

RQ2: How does spoon size affect bite size and usability when consuming different food forms? What is the range of spoon transformation for each food form that is optimal in minimising bite size and maximising usability?

3.1 Participants

We recruited 42 participants (20 males and 22 females) aged between 19 and 39 years (Mean= 24, SD=5) from the university's community after applying the following exclusion criteria: 1) medical conditions affecting chewing or food intake (e.g., hyperphagia), 2) currently on a specific diet, 3) vegetarianism , 4) allergies/intolerances to the served foods. All participants reported that the test foods were similar to what they frequently eat in their everyday lives and rated a liking score of at least 6 on a 10-point Likert scale (1- not at all, 10- extremely like).

3.2 Test Spoons

Spoon designs are influenced by culture and purpose of usage [4]. For instance, teaspoons (5ml) are traditionally made for stirring and sipping tea or coffee, while dessert spoons (10ml) are typically used for eating desserts, soup or cereals. On the other hand, tablespoons (15ml) are commonly used for serving and preparing food of larger size. We conducted a pilot study with 8 participants and discovered that both bite sizes and preferences were no longer affected when the spoon volume was larger than 16 ml. While spoon volumes less than 2ml were regarded as "useless" and "distracting". Therefore, we set 3 ml as the minimum volume size and 15ml as the maximum to be investigated in this study. Then, we fabricated a standard dessert spoon (10ml) by incrementally changing its volume from 3ml to 15ml (with 2ml interval) in X, Y, and Z dimensions. Figure 1 illustrates the 21 spoons (7 sizes $\times$ 3 dimensions) we 3D printed with food-grade material (PA2200 nylon). To minimize the influence of satiety and fullness on users' bite size and preference, we divided the spoons into 2 groups of similar total volume (M= 94.5; SD= 0.5). Group 1 includes *X7, X11, X13, Y5, Y9, Y13, Z3, Z7, Z11, and Z15* (*X7* refers to X dimensional change and spoon size equals 7 ml) and Group2 includes *X3, X5, X9, X15, Y3, Y7, Y11, Y15, Z5, Z9, and Z13*.

Fig. 1. The 21 test spoons used in Study 1. Each dimension has 7 different volumes ranging from 3ml to 15ml (with 2ml interval).

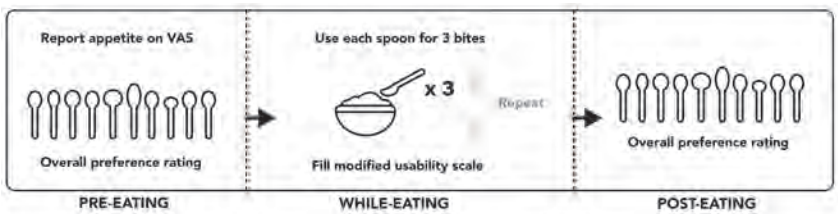

Fig. 2. The experiment procedure for each session of Study 1.

3.3 Test Food

Based on another pilot study with 8 participants, we observed that physical properties of food significantly influenced bite size and usability for different spoon shapes. For instance, for consuming breakfast cereals with milk, the extremely shallow spoons Z3 were sufficiently functional to hold a large number of cornflakes compared to the thin spoon X3 or short spoon Y3. In this study, test foods were selected based on three forms (i.e., solid, semi-solid, and liquid) [28] with two rationales: 1) they are commonly consumed, and 2) they are widely eaten with spoons. We chose steamed white rice for solid food, low-fat mixed berries yoghurt for semi-solid food, and chicken soup [86] for liquid food. Each of the 3 types of food was served in 400g, which is at least 45.2% larger than the standard portion size, to avoid "clear the plate" and over-consumption behaviours.

3.4 Procedure

The study was conducted over a total period of six different days (3 test foods × 2 spoon groups). For each day, participants were asked to evaluate one group of spoons for the same test food in three stages: (1) pre-eating, (2) while-eating, (3) post-eating, as shown in Figure 2. In the first step, participants rated their appetite and visually estimated their overall preference for each spoon using a 10-point scale. In the second step, we instructed participants to use one test spoon to consume three bites of test food and simultaneously rate them using an adapted usability scale [57]; this step was repeated until all test spoons for that day had been used. In the third and final step participants rated their overall preference, and we conducted a semi-structured interview to elicit a deeper understanding of the user's preference for using each spoon. Upon completing all six days, participants were reimbursed with a $10 Starbucks voucher.

3.5 Design

We used a within-subject design with spoon SIZE as a primary independent variable while spoon DIMENSION and food FORM as secondary independent variables. Spoon SIZE had 7 levels (3ML, 5ML 7ML, 9ML, 11ML, 13ML, and

15ML), spoon DIMENSION had 3 levels (DIM-X, DIM-Y, and DIM-Z), and food FORM has 3 levels (SOLID, SEMI-SOLID, and LIQUID). In terms of dependent variables, we measured *bite size* by using a hidden electronic scale to record the food intake in three bites and then divide the total weight of food consumed by three. We measured subjective feedback using a modified *usability* scale in terms of overall impression, shape satisfaction, volume satisfaction, easy-to-use, awkward-to-use, and willingness-to-use on a 5-point Likert scale (1- strongly disagree, 5- strongly agree). The experiment took six days to complete, with each day focusing on one group of spoon SIZES and one food FORM. We acknowledge that separating the experiment into 6 days might introduce a carryover effect; therefore, we asked the participants to maintain the same diet and fast (i.e, stop eating) for four hours before each visit and rated their *appetite* in terms of *hunger*, *fullness*, and *eating desire* on 100mm visual analog scales [23] (0: not at all, 100mm=extremely). We also counterbalanced the presentation orders for 1) spoon SIZES within a day and 2) food FORMS across the 6 days, to avoid any potential ordering effect. In summary, we recorded 42 participants × 3 spoon dimensions × 7 spoon sizes = 882 eating trials in total.

3.6 Results and Discussions

We first analysed the pre-meal appetite ratings using Wilcoxon signed-rank tests. Results showed no significant difference between participants' two days of visit on each aspect of *appetite* ratings (all $p > 0.05$). This means that we were able to maintain similar satiation levels across participants regardless of the different sets of spoon SIZES and food FORMS presented on each day.

Next, we revealed both the *bite size* and USABILITY measures in two sections, where each section focused on addressing one of the aforementioned research questions at a time. In each section, we also discussed how participants' comments complemented the objective results used to answer our research questions. As for quantitative analysis, we followed a similar methodology adopted by prior works [34]. We first checked the distribution of our *bite size* and *usability* measurement using Shapiro-Wilk. If data was normally distributed, we run the corresponding ANOVA and performed post hoc comparisons by conducting either pairwise t-tests (if bite size) or Wilcoxon signed-rank tests (if usability) with Holm corrections. Else, we conducted Friedman tests for *bite size* data that violates the normality assumption. When the assumption of sphericity was violated, we corrected both p-values and degrees of freedom using Greenhouse-Geisser ($\epsilon < 0.75$). To ensure meaningful and effective analysis between the 7 spoon SIZES, we first grouped the spoons into 3 CATEGORIES: **SMALL (3ML and 5ML spoons), MEDIUM (7ML and 9ML spoons), and LARGE (11ML, 13ML, and 15ML spoons)** to identify the optimal dimension before running more detailed pairwise comparisons between each spoon SIZE to determine the optimal range of transformation.

3.6.1 How Does Spoon Size Affect Bite Size and Usability across Dimensions of Transformation?

Three-way ANOVA revealed that there were interaction effects between spoon CATEGORIES, spoon DIMENSIONS, and food FORMS on both *bite size* ($F_{5.68,233.06} = 34.25$, $p < .001$, $\eta^2_G = .03$) and *usability* ($F_{5.61,233.15} = 10.74$, $p < .001$, $\eta^2_G = .18$).

Bite Size. We conducted two-way ANOVA and found interaction effects between spoon CATEGORIES and DIMENSIONS on *bite size* for all food FORMS (all $p < .0001$). As a result, we proceeded with analysing simple main effects and found that for each food FORM, there was a common trend demonstrated by each spoon DIMENSION: the SMALL spoons almost consistently contributed to a smaller *bite size* as compared to that of the MEDIUM and LARGE spoons (all $p < .001$). The only exception came from consuming SOLID food, where the MEDIUM and LARGE spoons did not contribute any significant difference ($t(41) = 1.33$, $p = .19$) in terms of *bite size* (see Fig. 3).

Usability. We also conducted two-way ANOVA and found interaction effects between spoon CATEGORIES and DIMENSIONS on *usability* for all food FORMS (all $p < .0001$). By analysing the simple effects for each food FORM, we found that the category of SMALL spoon sizes contributed to lower *usability* (all $p < .0001$) compared to that of the MEDIUM and LARGE spoons. While this trend (of smaller spoons attributed with lower usability) is expected, it

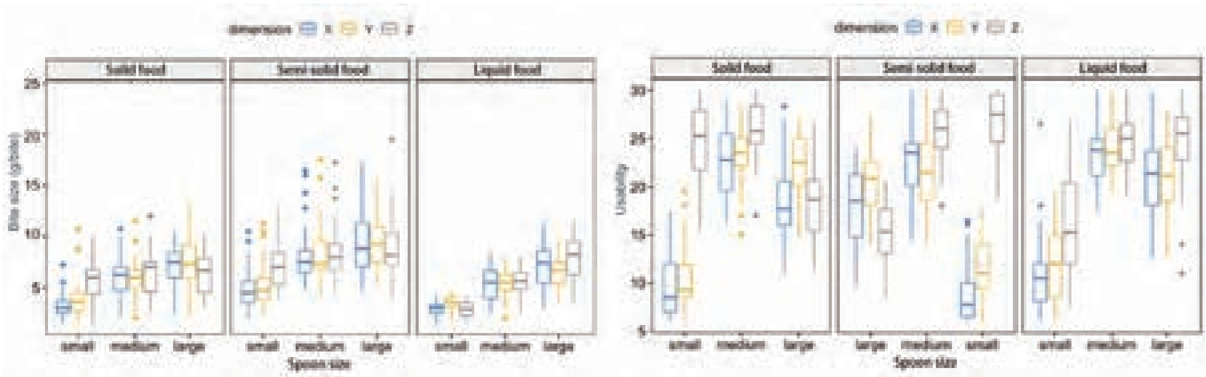

Fig. 3. *Bite size* (left) and *usability* (right) measures for each food FORM, each spoon CATEGORY, and each transformation DIMENSION.

is interesting to note how the SMALL spoons from DIM-Z were rated with higher *usability* than the respective spoons from DIM-X and DIM-Y (both $p < .0001$ and see Fig. 3).

Discussion on optimal dimension for transformation. From the results on *bite size*, we observed that the smaller spoons were able to deliver a much-reduced bite size across all three dimensions (X, Y, and Z). However, participants found that only in the Z dimension that the smaller spoons were able to achieve much higher usability than that from the X and Y dimensions. One reason could be due to the fact that spoons are often viewed from a top-down perspective; thus changes in the Z dimension might be visually less salient as compared to the other two dimensions. For instance, participants shared that "it looks more like a normal spoon, and it is somehow appealing compared to the rest." (P9). Another possible reason might be that using spoons in Z dimension change does not influence normal eating compared to other dimensions. As P27 commented, "as the spoons (i.e., X and Y) are small, I must stick my tongue inside in order to lick the food. It is both ineffective and indecent." Additionally, although changes in Z dimension lead to some extremely flat spoons, participants reported it is still "functional" because "it can hold enough food, especially for yoghurt and rice, where the food can stick to it." (P11). Integrating the above reasons, we chose the Z dimension as the optimal spoon transformation.

3.6.2 How Does Spoon SIZE Affect Bite Size and Usability across Food FORMS? With the previous results and discussions, we can now focus on analysing a more detailed relationship between spoon SIZE and food FORM for the identified Z dimension only. Two-way ANOVA showed that there are interaction effects between the two factors on both *bite size* ($F_{7.33,300.65} = 88.28$, $p < .00001$, $\eta^2_G = .46$) and *usability* ($F_{6.23,255.33} = 76.17$, $p < .00001$, $\eta^2_G = .44$). Therefore, each of the following subsections will analyse the simple main effect of spoon SIZE for each food FORM on both *bite size* and *usability*. At the end of each subsection, we also determine the optimal range of spoon transformation for each food FORM by considering the following principles:

(1) **We require both the lower and upper limit of the range to be rated with at least 18 total points.** This is assuming that out of the 5 points available in a Likert scale, a usability value of 3 can represent a neutral judgement for each of the 6 aspects. In this way, we are excluding spoon sizes that may potentially be considered undesirable by the general population to use.
(2) **To identify the lower limit of the range:**
  (a) We first select the smallest two spoon SIZES that adhere to the first principle as candidates.

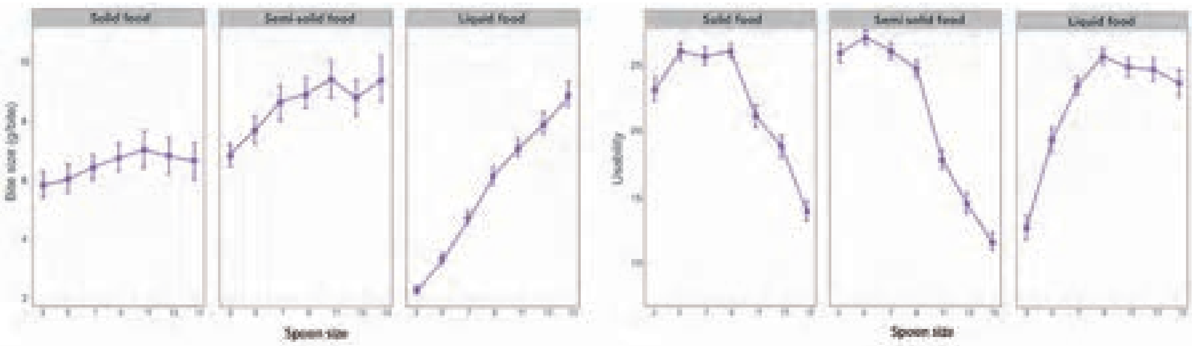

Fig. 4. *Bite size* (left) and *usability* (right) measures for each food form and each spoon size in the Z dimension.

(b) Then, if there is a significant difference in *bite size* between the two candidates, we will choose the smaller spoon size. This is because the primary goal of our dynamic spoon is to minimise bite size, thus the smaller, the better.
(c) else if there is no significant difference in *bite size* but significant difference in *usability*, we will choose the spoon with higher usability. In this case, the more positively users perceived the spoon, the better.
(d) else if there is no significant difference in both *bite size* and *usability*, we will choose the smaller spoon size as it has a higher probability of reducing bite size while maintaining usability.

(3) **To identify the upper limit of the range:**
(a) We first start with the lower limit identified by the second principle (say, 3ml) and compare it with a spoon one size larger (i.e., 5ml). If there is a significant difference in *bite size*, the next pair of adjacent sizes (5ml vs 7ml) were compared. This comparison is repeated until the pair shows no significant difference in *bite size*. This pair represents the spoon sizes that no longer influence bite size in any way.
(b) between the pair of adjacent sizes, if there is a significant difference in *usability*, we will choose the spoon with higher usability.
(c) else, we will choose the smaller spoon of the pair.

Solid Food. In terms of *bite size*, there was a significant simple effect of spoon size ($F_{3.01,123.69} = 6.39$, $p < 0.001$, $\eta^2_G = .019$). Pairwise comparisons found that both 3ml (m = 5.70 g/bite) and 5ml (m = 5.96 g/bite) contributed to a lower *bite size* (all $p < .05$) than all remaining spoons: 7ml (m = 6.36 g/bite), 9ml (m = 6.58 g/bite), 11ml (m = 6.79 g/bite), 13ml (m = 6.76 g/bite), and 15ml (m = 6.51 g/bite).

In terms of *usability*, there was a significant simple effect of spoon size ($\chi^2 = 127.17$, $p < .00001$). Pairwise comparisons found that the usability for 5ml to 9ml spoons were perceived to be similarly high (all $p > .05$), of at least 25.9 out of the maximum score of 30. In addition, there is a significant (all $p < .05$) decreasing trend of usability from 11ml (m = 21.2/30) to 13ml (m = 19.0/30) to finally 15ml (m = 14.6/30) spoons. Last but not least, the 3ml (m = 23.5/30) spoon is also perceived to be less usable ($p < .05$) than the 5ml (m = 26.0/30) spoon.

To determine the optimal range, we followed the above set of principles. Based on the first principle, we excluded 15ml spoon from the range. Based on the second principle, we chose 5ml spoon as the lower limit because although it contributed similar *bite size* with 3ml spoon, it was perceived more positively in terms of *usability*. Based on the third principle, we chose the 7ml spoon as the upper limit because there is no significant difference between the 7ml and 9ml spoons in terms of both *bite size* and *usability*.

Semi-Solid Food. In terms of *bite size*, there was a significant simple effect of spoon SIZE ($F_{3.9,159.77} = 14.48$, $p < 0.0001$, $\eta_G^2 = .089$). Pairwise comparisons found that both 3ML (M = 6.67 g/bite) and 5ML (M = 7.52 g/bite) contributed to a lower *bite size* (all $p < .05$) than all the remaining spoons: 7ML (M = 8.25 g/bite), 9ML (M = 8.48 g/bite), 11ML (M = 8.99 g/bite), 13ML (M = 8.45 g/bite), and 15ML (M = 8.96 g/bite). In addition, the 3ML spoon can lead to a smaller *bite size* compared to the 5ML one(p=0.002).

In terms of *usability*, there was a significant simple effect of spoon SIZE ($\chi^2 = 190.48$, $p < .00001$). Pairwise comparisons found that the usability for 3ML to 9ML spoons were perceived to be similarly high (all $p > .05$), of at least 25.1 out of the maximum score of 30. In addition, there is a significant (all $p < .05$) decreasing trend of usability from 11ML (M = 18.3/30) to 13ML (M = 14.9/30) to finally 15ML (M = 12/30) spoons.

Furthermore, to determine the optimal range, we followed the above set of principles. Based on the first principle, we excluded 13ML and 15ML spoons from the range. Based on the second principle, we chose the 3ML spoon as the lower limit because it contributed to the smallest *bite size*. Furthermore, based on the third principle, we chose 7ML spoon as the upper limit because there is no significant difference between the 7ML and 9ML spoons in terms of both *bite size* and *usability*.

Liquid Food. In terms of *bite size*, there was a significant simple effect of spoon SIZE ($F_{3.06,125.48} = 184.43$, $p < 0.0001$, $\eta_G^2 = .6$). Pairwise comparisons found that the smaller the spoon SIZE, the smaller the *bite size*, all at the (p<0.001): 3ML (M = 2.25 g/bite), 5ML (M = 3.38 g/bite), 7ML (M = 4.67 g/bite), 9ML (M = 5.92 g/bite), 11ML (M = 6.93 g/bite), 13ML (M = 7.67 g/bite), and 15ML (M = 8.51 g/bite).

In terms of *usability*, there was a significant simple effect of spoon SIZE ($\chi^2 = 117.95$, $p < .00001$). Pairwise comparisons found that the usability for 9ML to 15ML spoons were perceived to be similarly high (all $p > .05$), of at least 25.0 out of the maximum score of 30. In addition, there is a significant (all $p < .05$) decreasing trend of usability from 7ML (M = 23.9/30) to 5ML (M = 19.3/30) to finally 3ML (M = 12.8/30) spoons.

Moreover, to determine the optimal range, we followed the above set of principles. Based on the first principle, we excluded the 3ML spoon from the range. Based on the second principle, we chose the 5ML spoon as the lower limit because it contributed to similar bite size *bite size* with the 3ML spoon; yet, it was perceived more positively in terms of *usability*. Lastly, based on the third principle, we chose the 9ML spoon as the upper limit because it was perceived more positively in terms of *usability*.

Please refer to Fig. 4 for full illustration and Appendix A.1 for full statistical reports.

4 *SSPOON* PROTOTYPE DESIGN AND DEVELOPMENT

Using the insights from Study 1, we developed and fabricated *SSpoon*, a shape-changing spoon that alters the food-carry volume (i.e., the spoon head becomes shallower or deeper) to directly influence the bite size. The *SSpoon* consists of two main components: 1) an inflatable membrane attached to the spoon head, 2) a pneumatic control system embedded within the spoon handle.

4.1 Design of Inflatable Membrane

The main role of the inflatable membrane is to change the food-carry volume of the spoon. We chose silicone as the material due to the following reasons: First, as compared to other elastomers, silicone is one of the most widely used materials for spoons due to its food-safe properties [60]. Second, silicone of different shore hardness is commercially available, which enables us to precisely manufacture and control their physical properties (e.g., volume change); thus, making it easier for future work to adopt our design. Four types of rubber silicone products from Smooth-On Inc were tested: Ecoflex 00-50, Dragon Skin-10, Dragon Skin-20, Dragon Skin-30 using an image analysis tool called Image J [1]. Ecoflex 00-50 was chosen due to its flexibility to achieve a well-controlled deformation ratio from 31% to 157%. The fabrication process followed the basic procedure similar to [31], where mixed silicone reagents were poured into food-safe PLA moulds to be printed using an FDM 3D printer.

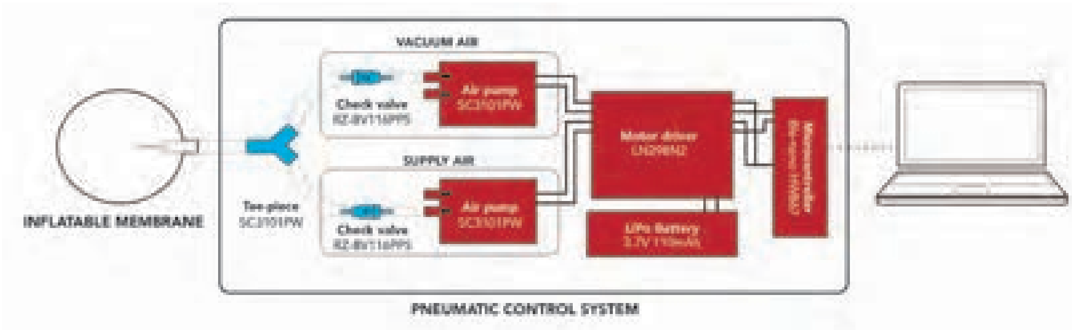

Fig. 5. Schematics of *SSpoon*'s electronic components.

4.2 Design of Pneumatic Control System

The objective of the pneumatic control system is to supply and vacuum air into the membrane. Given the development of soft robotics, applying soft, malleable, and elastomer material connected to pneumatic control systems creates new possibilities for dynamic shape change [78]; thus, becoming the preferred solution to support our *SSpoon* design transformation. Figure 5 illustrates the pneumatic control system which incorporates a ventilation duct to supply and vacuum the air pressure from the inflatable membrane. Two air pumps(SC3101PW) were used to control the airflow into three modes: expansion, contraction, and close. The first two modes function as inflating/deflating air into the membrane, while the last mode prevents the air from escaping the membrane. To drive the air pumps and check values, we used the motor drivers (LN298N2) through the PWM output, powered by a lithium polymer battery (3.7V, 100mAh). The noise levels of the systems are 54 dB (for inflating air) and 56 dB for deflating air), which are safe and acceptable for daily life [53].

4.3 Design of Spoon Handle

Integrating pneumatic actuation components into a spoon could result in an abnormally enlarged handle shape, thus affecting user adoption. Therefore, this pilot study aims to determine the ideal handle design that optimises the user's preferences despite the unconventional shape. To achieve this aim, two steps are included in this study.

4.3.1 Approach. Firstly, we conducted in-the-wild observations with 100 university members holding a standard spoon while consuming their meals. The results indicated that 89% of the participants held the back portion of the handle while 11% held the middle part. This result informed us that the morphology of the back half of the spoon handle plays a more important role compared to the front half. Secondly, we prototyped six handle designs and evaluated them over a user study with 12 participants (6 females) to gain a better understanding of their perceptions and preferences of spoon handles.

4.3.2 Design Considerations. Either linear or clustered distribution can be used to connect the ventilation duct and the electronic driver, as shown in Figure 6. For linear distribution, by adjusting the top surface of the spoon, we generated two design variants (i.e., L1 and L2); while, for clustered distribution, we have the option to cluster the front or back portion of the spoon in either a symmetrical or asymmetrical way, resulting in four designs (F1, F2 and H1, H2).

4.3.3 User Study. We asked eligible participants to try one prototype at a time and rated (1="strongly disagree" and 5="strongly agree") on its aesthetics, functionality, and symbolism on a modified product design scale [41].

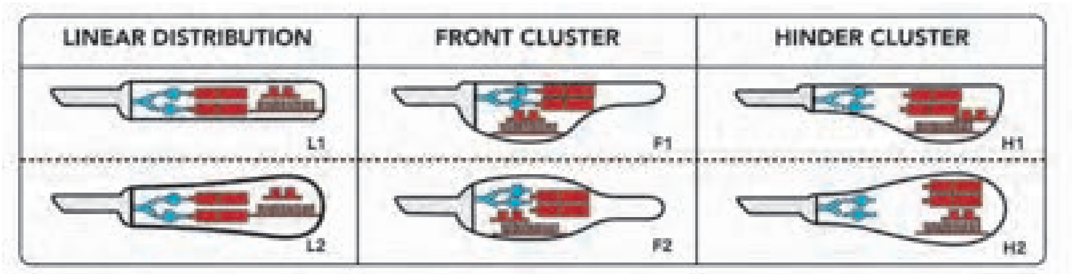

Fig. 6. Six spoon handle designs based on different arrangement of ventilation duct (in blue) and electronic driver (in red).

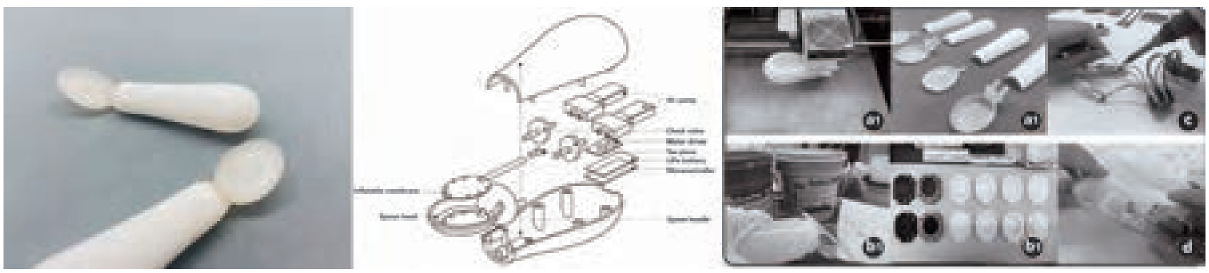

Fig. 7. The fabrication and final prototype of *SSpoon* includes (a) 3D printing; (b) multiple moulding and casting; (c) wire soldering; (d) assemble. Main body part of the *SSpoon* was 3D printed using dental SG resin for food safety.

The order of the prototypes was counterbalanced using the Latin Square to minimise the order effect. After using all six prototypes, we asked the participants to rank them(1="most liked" and 6="most disliked").

4.3.4 Subjective Results. A non-parametric Friedman test demonstrated a significant difference in the overall user ratings among the six prototypes ($p<0.000$). Wilcoxon signed rank test with Bonferroni correction revealed that L2 had significant higher overall usability ratings as compared to F1($p=.004$), F2($p=.003$), H1($p=.003$) or H2($p=.01$). Although there was no significant difference between L1 and L2 ($p=0.1$), participants preferred L2 ($M=34$, $SD=5.46$) over L1 ($M=30.67$, $SD=4.03$). For ranking data, an analysis using the sumproduct formula showed a consistent result that L2 (score=17) achieved the highest overall user preference ranking ($M=43.8$, $SD=6.8$). These results indicated that prototype L2 was perceived most positively among the six prototypes. This is frequently reported that linearly connecting the ventilation duct and the electronic driver results in an "even distribution of weight" (8/12); thus, participants felt more "natural to use" (8/12). In addition, as compared to the relatively flat prototype L1, the smooth edge of L2 is not only "appealing"(P7) but also "perfectly fits the anatomical features of the hand" (P2). Prototypes B1 and B2 were criticised as “too large and uncomfortable” (7/12) to hold, while prototypes F1 and F2 were front-heavy. Most participants (9/12) reported "loss of motor control" when scooping the food and described the aesthetic as "out of what the general population may assume as a spoon" (P12).

Based on the above implementation and user evaluation, we proposed the final design of *SSpoon* (see figure 7) with L2 design and evaluated its effectiveness in a more realistic scenario in Study 2.

5 STUDY 2: IMPACT OF SSPOON ON ORAL PROCESSING BEHAVIOUR, APPETITE, AND USABILITY

Our previous Study 1 (see Section 3) suggests that the reduction in the food-carrying volume of the spoon's head in the Z dimension could effectively limit the bite size while maintaining the spoon's usability; and that there is also an optimal range of transformation for each food form. Accordingly, we define shape-changing feature as the ability for the spoon to dynamically decrease its volume from the optimal maximum size to the optimal minimum size. The rationale is derived from the results from Study 1 which revealed that users have a strong habit of using a standard eating spoon and are reluctant to use a small spoon to eat. However, psychological and economic studies demonstrated that humans do estimate their food consumption based on indirect cues; such as the size of a plate and the size of a package [13, 81–83]. Thus, we hypothesised that by dissociating the visual feedback of spoon size (i.e., optimal maximum) from the actual bite size users took (i.e., optimal minimum) may alleviate their reluctance to use a spoon with a smaller food-carry volume.

However, without a study, it is difficult to understand how exactly a dynamic spoon could influence the overall eating experience. Therefore, we conducted the second study to investigate the impact of our proposed system - *SSpoon* - in a realistic eating scenario and how does it compare with the traditional static spoon currently used on a daily basis. Specifically, we aim to investigate the following three research questions:

RQ3: How does *SSpoon* affect the eating rate and other oral processing behaviour during a meal containing different food forms?

RQ4: How does *SSpoon* affect perceived appetite?

RQ5: How does *SSpoon* affect user perception of the overall eating experience?

5.1 Participants

We recruited 16 participants (10 females and 6 males) with an age range from 21 to 33 (average= 25.4) and had a body mass index (BMI) of 20.94 ± 0.17 (range= 18.3 to 24.2) after applying the exclusion criteria similar to Study 1. All participants reported that the test food was similar to what they frequently ate in their everyday lives and that they rated a liking score of at least 6 on a 10-point Likert scale.

5.2 Test Food

Each meal consisted of three types of food varying in their physical forms and purposes. Specifically, we want to include solid, semi-solid, and liquid food, and food serving different purposes (main course vs. soup vs. dessert). The full course meal used in the study included: beef fried rice as the main course (solid), miso soup as a side dish (liquid), and vanilla pudding as the dessert (semi-solid). Each food was served in a larger portion, which is 50% larger than a standard portion size in order to avoid "clear the plate" behaviour [80]. Such behaviour is undesirable because it could result in participants eating more food than required.

5.3 Test Spoons

We used two types of spoons: a *SSpoon* and static baseline spoons of size 5ml and 10ml. For the *SSpoon* condition, we simulated the dynamic transformation of the spoon shape using a Wizard-of-Oz approach [14] to evaluate the concept without technological restrictions. The experimenter would remotely control the spoon volume depending on what food is being scooped by the participant. Participants only needed to use one *SSpoon* for the entire meal with three different types of food. For the baseline spoon condition, we comply with the standard dining etiquette and habits [61] by providing: 1) a small spoon of 5ml for the consumption of pudding and 2) a large spoon of 10ml for the consumption of both rice and soup. The key difference between *SSpoon* and the baseline spoons is that the latter is static; thus participants would have to manually change the spoon depending on what they are consuming. Regardless of the condition, all three spoons were 3D printed using biocompatible material (Dental SG) to minimise potential confounding effects. This material is different from the one used in Study 1 in order to enhance the finishing quality of the spoon prototypes.

5.4 Procedure

The study was conducted over two days, each focusing on one spoon condition. Similar to Study 1, participants were instructed to maintain the same diet and fast for four hours before each visit to standardise the satiety state. We ensured that the two-day visits were within the same lunch (11 am to 1 pm) or dinner (5-8 pm) hours. In each visit, there were four steps that each participant had to follow. First, they had to complete a pre-meal questionnaire using a VAS scale. This is for us to collect their perceived hunger, fullness, and desire to eat. Second, they wore a wireless headphone (SONY) that played restaurant background music. Our purpose is not only to simulate a naturalistic eating experience but also to minimise the noise generated by the electronic driver when *SSpoon* changes its shape. Third, the experimenter would serve the meal in two separate stages: (a) rice and soup together and (b) dessert, before instructing participants to eat the meal naturally. The experimenter also informed them they could stop whenever they were comfortably full and did not have to clear the plate. For the last step, participants rated their post-meal appetite through a questionnaire. At the end of the second day, we asked participants their overall preference for using each spoon. The entire study across two days was video recorded for further analysis of oral processing behaviour. We also counterbalanced the presentation order between *SSpoon* and baseline spoon to avoid any potential ordering effect.

5.5 Design

We used a within-subject design with SPOON as the independent variable, with two levels (SSPOON and BASELINE). In terms of dependent variables, we measured *oral processing behaviour* by analysing the recorded video using a behavioural annotation software (ELAN 6.1) [3]. It has been validated to show good correspondence with EMG recordings of oral muscle activity during eating without interrupting the real-life eating behaviour [85]. We followed the same coding scheme used by prior studies [10, 21, 24] and recorded the number of bites and swallows that occurred during eating. Table 1 lists and defines the nine parameters that the *oral processing behaviour* can be further decomposed into. We also measured participants' *appetite* by reusing the same rating used in Study 1. For subjective feedback, we used a modified *usability* scale [20, 22] in terms of *overall impression*, *easy to use*, *comfortable to use*, *natural to use*, and *willingness to use frequently* on a 7-point Likert Scale (1: strongly disagree, 7: strongly agree). In addition, using the same scale, we also asked participants for their *perceived reduction in eating rate*, i.e. whether they thought each spoon helped them slow down their usual eating rate.

5.6 Results

The assumption of normality was tested using Shapiro-Wilk ($p > .05$). Either paired-sample t-tests or Wilcoxon signed-rank tests (if normal distribution is violated) were performed on each parameter of oral processing behaviour, appetite ratings and subjective ratings.

5.6.1 Oral Processing Behaviour. There was a significant effect of SPOON on *food intake*, *oral exposure time*, *number of bites*, *bite size*, *oral exposure per bite*, *eating rate*, and *length of pause/interval*, all at the $p < .05$ level. However, no significant difference was found in *meal duration* ($t = -1.9$, $p = .065$) and *percentage of actively consuming food* ($Z = 34$, $p = .083$) between the two SPOONS. We elaborate on three key oral processing behaviour results which can be referred to Figure 8.

Food intake. There was a significant effect of SPOON ($t(15) = 4.70$, $p < .001$) on *food intake*. Particularly, using SSPOON (560.88 ± 128.543) could decrease food consumption by 4.4%, as compared to using the BASELINE spoon (586.88 ± 134.81).

Table 1. Coding scheme for oral processing behaviour

Oral processing behaviour	**Definition**
Food intake (g)	Total amount of food consumed.
Meal duration (s)	Time between the first pick up spoon and the last drop of the spoon.
Oral exposure time (s)	Cumulative time food spent in the mouth between the bite and the swallow throughout the meal.
Number of Bites	Total number of bites.
Bite size (g/bite)	Total amount consumed divided by the total number of bites.
Oral exposure per bite (s/bite)	Total oral exposure time of food in mouth across the meal, divided by the total number of bites.
Eating rate (g/s)	Total amount of food consumed divided by the total oral exposure time.
Average length of pause/interval	Total non-active eating duration divided by total number of interval (s)
Percentage of actively consuming food (%)	The ratio of total oral exposure time to the total meal duration

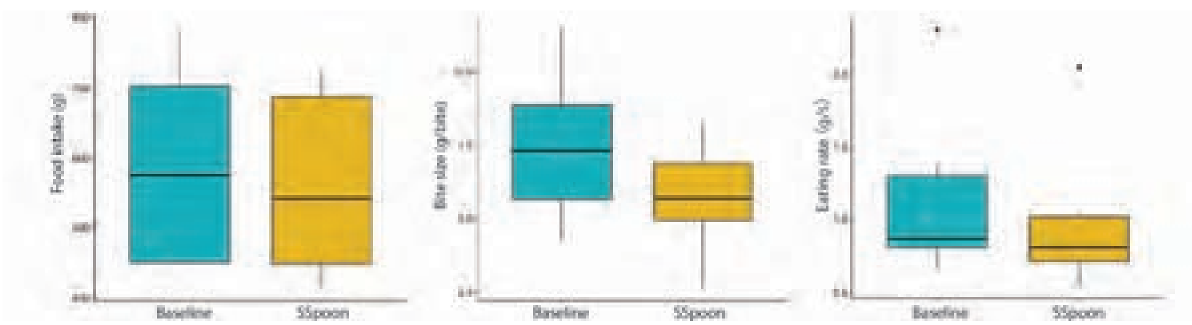

Fig. 8. The 3 key measures forming *oral processing behaviour* across all 16 participants.

Bite size. There was a significant effect of SPOON ($t(15) = 6.39$, $p < .001$) on *bite size*. This means participants had smaller (6.6%) bites while using SSPOON (5.78 ± 1.78) as compared to the BASELINE spoon (7.39 ± 2.47).

Eating rate. There was a significant effect of SPOON ($t(15) = 4.69$, $p < .001$) on *eating rate*. In general, participants were able to slow down their eating rate by 13.7% when using SSPOON (0.96 ± 0.46) as compared to using the BASELINE spoon (1.11 ± 0.53).

These results provide answers to **RQ3**, namely that SSpoon could have a significant impact on oral processing behaviours by decreasing the bite size, prolonging exposure time, and decreasing the eating rate. Despite the increase in the number of bites and the reduction in oral exposure per bite when using *SSpoon*, the overall food intake decreased.

5.6.2 Appetite Rating. There was no significant difference of SPOON in *appetite rating* in terms of *hunger* ($t(15) = 0$, $p = 1.0$), *fullness* ($t(15) = -0.99$, $p = .34$), and *desire to eat* ($t(15) = -0.99$, $p = .34$). These results provide initial evidence to answer **RQ4**, suggesting that *SSpoon* may not influence the perceived appetite despite decreasing the overall consumption of food in a standardized meal.

5.6.3 Subjective Rating. There were no significant differences (all $p > .05$) of SPOON across all subjective rating measures (see Appendix A.2).

Perceived reduction in eating rate. While overall perception seems to suggest that both spoons are comparable in terms of eating rate, we dig deeper into the nuanced differences we observed between food forms. 10 out of 16 participants expressed that using *SSpoon* allowed them to eat more slowly than the baseline spoon. The most likely explanation is that the flatter surface of the spoon gave them less food, especially when it comes to consuming soup, where the amount of liquid highly depends on the spoon size compared to other food forms. However, 4 of 16 participants believed that both spoon conditions were similarly effective for slowing down their rating because they could not differentiate between the two spoons. As P8 reported, "I did not notice any difference between the spoon I used yesterday and today". This is because for rice and yoghurt, the relatively sticky texture allows food to exceed the expected volume of the spoon, thus allowing the shallower *SSpoon* to scoop a similar amount as compared to the deeper baseline spoon.

Ease of use. 12 of the 16 participants preferred *SSpoon* over the baseline, while two participants did not have a preference. One of them explained that scooping rice with a flat surface of the *SSpoon* was easier because the food did not stick at the bottom, and they could easily empty the spoon using their lips or tongues. Furthermore, since rice tends to stick together, they felt that the shallower spoon did not affect the amount of food they took in any way. Not to mention that the rice was served as the main course, which played a significant role in the overall meal experience. The above reasons suggest why they could be more inclined to prefer *SSpoon* in terms of ease of use.

Comfortable and natural to use. Only 6 out of 16 participants found the *SSpoon* to be more comfortable and natural to use, while 4 said that both spoons were similar. Despite our attempt to optimise designs for the spoon head and handle in Section 4, the abnormal handle of the spoon was the most frequently mentioned concern by participants who had to use SSpoon first before the baseline spoon. A majority (62.5%) of participants blamed the relatively bigger handle (as compared to their normal daily spoon) for the difficulty in holding the spoon. However, not all participants disliked *SSpoon*'s abnormal shape. For example, P10 thought the handle "looks cute" which enhances their overall eating experience and P6 commented, "although there was a difference between the handles, I don't think it makes much difference to me when I am eating. The top part [food-carrying part] of any spoon has little influence in my eating experience". One participant even reported that "I feel (the handle) perfect fit, maybe because I tend to hold from the top". 80% of participants reported that they were familiar with using the initially abnormal handle by the second day of experiment, as P1 mentioned: "I am getting used to its shape and weight of the spoon after trying both spoons". Although incorporating electronic components makes the *SSpoon* shape unique as compared to the traditional spoons, it is nevertheless easy to adopt in practice. In considering why more than half of participants understated the comfort and natural attributes of *SSpoon*, one frequently mentioned reason is related to soup consumption. Due to the extremely small size of the spoon, which is only half of the baseline size for soup, it significantly affected how much soup the participants could scoop. Additionally, eating involves two gestures: 1) scooping the food from the container and 2) inserting the spoon into the mouth. As the liquid food was easily spilt over the spoon, this process became "unsatisfactory and a bit annoying". While the soup consumption is challenging for some participants, it didn't skew their overall preference for *SSpoon* because some of our participants generally drink soup from bowls rather than using spoons. Therefore, spoon itself may cause some obstruction, regardless of whether they use a standard spoon or our proposed *SSpoon*. According to P13, "I typically do not drink soup with a spoon, it is the same for me with any spoon".

Willingness to use frequently. Half of the participants preferred *SSpoon*, and the median rating of *SSpoon* was 5, which is higher than that of the baseline, which was 4. This indicated that people were not reluctant to use *SSpoon* despite its smaller volume compared to traditional eating spoons. Particularly those participants who identified as fast eaters yet understood the negative consequences of fast eating on their health reported that the unique feature of slowing down their eating rate increased their acceptance and willingness to use *SSpoon* in their daily eating.

In terms of *overall impression*, half of the participants chose *SSpoon* over the baseline spoon as their preferred spoon. Based on the abovementioned findings, **RQ5** can be answered. That is, despite the small food-carry volume and unusual shape offered, *SSpoon* may be comparable to the static spoon in terms of usability and user preference, suggesting great potential for future adoption.

5.7 Discussion

5.7.1 Introducing Subtle Changes in the Transformation Could Encourage Desirable Eating Behaviors. Study 2 simulated an ideal condition in which participants scooped the food, and the *SSpoon* detected the food form and directly changed from the maximum optimal scoop size to the minimum optimal scoop size as observed in Study 1. While the general user's perception is comparable to the standardized size spoon condition, some negative comments were reported using *SSpoon* for soup consumption. This is due to the extremely small volume and fluidity of liquid food which led to the participants struggling to hold soup inside the spoon without spilling over, which therefore decreased their preference for using *SSpoon*. Therefore, there is a need to explore additional design parameters to alleviate the issues with using *SSpoon* for liquid food consumption. A promising design parameter is the rate of transformation; that is, rather than an instant adjustment from the optimal maximum size to the optimal minimum size, a subtle, incremental reduction in volume might be an effective solution. This was investigated further in Study 3.

6 STUDY 3: OPTIMAL RATE FOR SSPOON AND VALIDATING ITS BENEFITS

Our previous Study 2 demonstrated the feasibility and benefits of using *SSpoon* over a standardised spoon; yet, the shape-changing mechanism used was relatively simple: the spoon size changes instantly based on the detection of food form and remains unchanged during consumption. In addition, there exist many ways to design the shape changing mechanisms. For example, one can imagine a gradual and subtle change of spoon size during a meal. This approach starts with a normal size spoon when users are the most hungry to greatly preserve the normal eating experience and over time, the gradual reduction of spoon size could help to achieve the similar benefits of a small spoon. The advantage of this approach is that it can be used for a more versatile eating style. In many cultures, people eat food in mixed forms throughout the meal (e.g., one bite of solid food, followed by one drink of the soup, followed by another bite of solid food, etc.). Under such eating styles, changing the spoon size based on only food form may not produce the optimal experience as the change will be too frequent. On the other hand, our proposed strategy of a more gradual changing of spoon size throughout a meal can better accommodate individual eating styles. To identify the optimal shape changing strategy for this approach, two questions need to be addressed: How much (i.e., the reduction volume interval) and How fast (i.e., the reduction speeds), which can be formulated into the following three research questions.

RQ6: How do reduction volume **intervals** affect user's preference and perception?

RQ7: How do reduction **speeds** affect oral processing behaviour while maintaining user perception of subtlety?

RQ8: How would a dynamic *SSpoon* compare with static spoons (both normal and small) in terms of oral processing behaviour and user perception of the overall eating experience?

These questions investigate the tradeoff between subtlety and effectiveness of a dynamic *SSpoon*. From one perspective, a subtle change may create a visual perceptual bias to help alleviate people's reluctance to use a small spoon for eating. On the other hand, this change could also be less effective in limiting bite size and influencing oral processing behaviour, as compared to a normal spoon. We conducted a sub-study for each of the above research questions and will discuss the results in the next Section 7, together with insights from Studies 1 and 2.

6.1 Sub-Study 3.1

In this sub-study, we investigated the optimal volume of *SSpoon* to be reduced at each time, such that the change from a standard eating spoon size to a small spoon size is subtle and preferred by users. Similar to Study 2, we conducted this in a Wizard-of-Oz fashion. The main difference is that in this study, we transformed the *SSpoon* using a manual air pump instead of the pneumatic driver used in Study 2. We applied this enhancement because Study 2 participants reported that the noise and vibration produced by the electronic driver could bias their perceived utility of *SSpoon* [30].

6.1.1 Reduction Trigger. Before diving into how much volume to be reduced at each time, we first conducted a pilot study to investigate **where** the change can be triggered as naturally as possible. The results of 8 participants indicated that changing the spoon size **after** each bite was perceived as the most natural, unobtrusive, and preferred over changing it **while** the spoon was inside one's mouth. Hence, we adopted the strategy of triggering each change after a bite for all the subsequent sub-studies.

6.1.2 Reduction Intervals. Then, we conducted another pilot study which revealed that when a one-time reduction interval is greater than 4ml, participants considered it as “disruptive” and “awkward”. Therefore, in this Sub-Study 3.1, we chose to examine the effects of smaller reduction intervals (1ml, 2ml, and 3ml) on user's perception and preference. We also set the maximum reduction volume to be 6ml (instead of 5ml) because it is a multiple of all the three values and thus could accommodate all three reduction intervals. Regardless of the volume intervals, our test spoons consistently would be transformed from a maximum of 10ml (normal spoon size) to a minimum of 4ml.

6.1.3 Test Food. According to our previous studies, food form has a significant impact on users' perception of spoon size. In particular, the volume of liquid food that one can scoop is significantly reduced when a smaller spoon is used, as compared to the volume of solid and semi-solid food. Thus, participants expressed more negative feedback when using *SSpoon* for liquid food. In this study, we chose to focus on this more challenging liquid form (i.e. miso soup) to identify the upper limit of the reduction interval, in order to ensure participants perceived the change across all food forms as subtle and acceptable as possible.

6.1.4 User Study. We instructed 12 participants (10 females and 2 males) to consume the soup using *SSpoon*, with three different reduction intervals. After each interval, participants rated their *SSpoon* perceptions in terms of *subtlety*, *naturalness*, *annoyance*, and *disruptiveness* using a 7-point Likert Scale (1: strongly disagree, 7: strongly agree). The order of reduction intervals was counterbalanced to minimise the order effect. After trying all three intervals, participants ranked their overall preference (1= "most liked"; 3= "most disliked"), followed by a semi-structured interview to elicit a deeper understanding of their preferences.

6.1.5 Results. A non-parametric Friedman test demonstrated significant effects of reduction intervals on *subtlety* ($\chi^2 = 17.6, p < .001$), *naturalness* $\chi^2 = 17.2, p < .001$, *annoyance* $\chi^2 = 10.2, p < .001$, and *disruptiveness* $\chi^2 = 15.5$, $p < .001$). Pairwise comparison, using Wilcoxon signed rank test with Bonferroni correction, revealed that participants perceived the 1ml (median=7) and 2ml (median=6) to be more subtle than the 3ml (median=3, all p <.03), perceived the 1ml (median=6.5) and 2ml (median=5.5) to be more natural (all $p = .02$) than 3ml (median=3), and perceived the 1ml (median=1) to be less disruptive ($p = .03$) than the 3ml (median= 3.5). In general, subjective ratings for 2ml were lower than those for 1ml (see Fig. 9), although no significant difference was found.

Overall, 11 out of 12 participants chose 1ml over 2ml as their preferred reduction interval for spoon change. The only exception was because the participant has a habit of taking small sips rather than finishing the whole

Fig. 9. Subjective ratings between three spoons of varying reduction volume INTERVALS.

scoop. Therefore, she did not notice the subtle differences between 1ml and 2ml. Participants who preferred 1ml explained that "it is very gradual, and I actually did not notice anything at all in the first three bites" (P3) (similar opinion from 8 other participants). We can now answer **RQ6**: reduction intervals of 1ml and 2ml were perceived as being more subtle, natural, less annoying, and less disruptive than that of 3ml. Moreover, all except one participant preferred 1ml over 2ml; thus, we selected 1ml as the optimal volume interval for *SSpoon* dynamic reduction.

6.2 Sub-Study 3.2

The results from Sub-Study 3.1 show that changing the spoon size at a rate of 1ml after each bite (i.e. spoon has left one's mouth) was not only more subtle but also more preferred by participants. However, it is still unclear how fast the *SSpoon* transformation should be to effectively influence the oral processing behaviour while retaining the perceived subtlety.

6.2.1 Participants. 18 participants (9 females and 9 males), aged 20 to 27 (M = 23.7, SD = 2.7) with a body mass index (BMI) of 18 to 27 (M = 21.8, SD = 3.3) were recruited with the same exclusion criteria of Study 1. The proportion of the participants who are considered overweight ($25 \leq$ BMI ≤ 35) is 33.3%, which is consistent with the World Health Organization (WHO) classification [75].

6.2.2 Test Food. In addition to the soup used in the previous Sub-Study 3.1, we included beef fried rice (i.e. solid food) because such additional main course would be more realistic than asking participants to only drink soup. Since both soup and rice share the same minimum spoon size recommendation of 5ml(identified in study 1), the *SSpoon* transformation throughout the entire meal would be from 10ml (normal spoon size) to 5ml.

6.2.3 Reduction Speeds. Studies in clinical psychology and behavioural science demonstrated that eating behaviour is characterised as either **decelerated** or **linear**, depending on how the eating rate changes over the course of a meal [98]. **Decelerated eaters** typically show a higher initial eating rate due to a larger bite size in the first half of the meal, followed by a drop in eating rate in the second half. **Linear eaters** exhibit a low eating rate at the beginning of the meal, which remains relatively stable throughout the meal. Intuitively, implementing change during the first half of the meal could have a greater impact on controlling the eating rate and also overall reduction in food consumption across all types of eaters. For example, if we intend to change the spoon size from 10ml to 5ml during the first half (50%) of the meal, we can also vary the speed: in the slowest case, it can take the entire first half of meal time to make such changes (or 50%), or one can double the speed to implement the change using half of time (50%/2 = 25%), or quadruple the speed (12.5%), or eight times the speed (6.25%), etc. However, note that there is a practical limit to how fast we can make such changes. Since each 1 ml can only happen after each bite, thus it requires at least 5 bites to change from 10 ml to the 5ml; therefore, the fastest speed should be bounded by the amount of food one will take with 5 bites. Results from Study 2 showed that the percentage of meals consumed by 5 bites accounted for 1.9-12.3% of overall food intake. Hence, 6.25% was discarded from the testing conditions and only 50%, 25% and 12.5% were selected for study. Additionally, in order to determine if changes in the reduction speed could influence the oral processing behaviour, a comparison with a static spoon (10ml) as a baseline was performed.

6.2.4 Customising Reduction Speeds. Food intake varied among individuals [15], making it inaccurate to base the above reductions speeds on one assumed food intake amount across all participants. Since previous work established a consistent amount of food intake within an individual [63], we have to customise the reduction speeds based on individual normal food consumption. For example, let's assume that we measured a participant's normal food consumption to be at 400 g. For *SSpoon* to complete the total 5ml reduction within the first 25% of food intake (i.e., the first 100g), this means that each 1ml reduction should occur approximately at the 20g, 40g, 60g, 80g, and finally at the 100g mark of user food consumption.

6.2.5 Procedure. The study was conducted over four days at a fixed time slot. The first day of the experiment was used as a familiarisation trial, in which we transformed *SSpoon* into a normal static eating spoon to determine each participant's normal food intake. On each subsequent days, we instructed participants to follow the same four steps introduced in Study 2: one reduction speed per day. For each reduction speed, the experimenter continuously monitored the participant's cumulative food intake using a weighing tray and remotely controlled the *SSpoon* volume.

6.2.6 Design. We used a within-subject design with reduction SPEEDS as the independent variable, with four levels (BASELINE, 50%, 25% and 12.5%). In terms of dependent variables, we measured oral processing behaviour using video analysis (same as Study 2) and measured participants' appetite (by using the same scale as in Study 1). For subjective feedback, we reused the 7-point Likert scale used in the Sub-Study 3.1.

6.2.7 Results. The assumption of normality was tested using Shapiro-Wilk ($p > .05$). Either one-way repeated-measures ANOVA or Friedman test (if ANOVA assumptions are violated) was performed on each parameter of oral processing behaviour, appetite ratings, and subjective ratings. The post hoc comparison by conducting with either pairwise t-test or Wilcoxon signed-rank tests with Bonferroni corrections were performed.

There were significant effects of reduction SPEED on *food intake*, *number of bites*, *bite size*, and *eating rate*, all at the $p < .05$ level. However, no difference was found in *meal duration* and *percentage of actively consuming food* between the three reduction SPEEDS. Below, we elaborate the key results relating to oral processing behaviour see figure 10.

Food Intake. There was a significant effect of reduction SPEED ($\chi^2 = 9.4$, $p = .02$) on *food intake*. Pairwise comparisons indicated that all three reduction speeds could decrease (all $p < .001$) food consumption as compared to using the baseline speed (436±79.5). However, there is no significant difference ($p > .05$) between 50% (368±59.1), 25% (378 ± 87.1), and 12.5% (380 ± 80.6).

Bite Size. There was a significant effect of reduction SPEED ($\chi^2 = 15.8$, $p < .001$) on *bite size*. Pairwise comparisons indicated that participants took a smaller $p < .001$ *bite size* in all three reduction SPEEDS as compared to the baseline speed (7.08 ± 1.66). Additionally, the reduction speed at 12.5% (4.17 ± 0.687) significantly outperformed ($p = 0.01$) the one at 50% (5.07 ± 1.25) in terms of reducing the *bite size*.

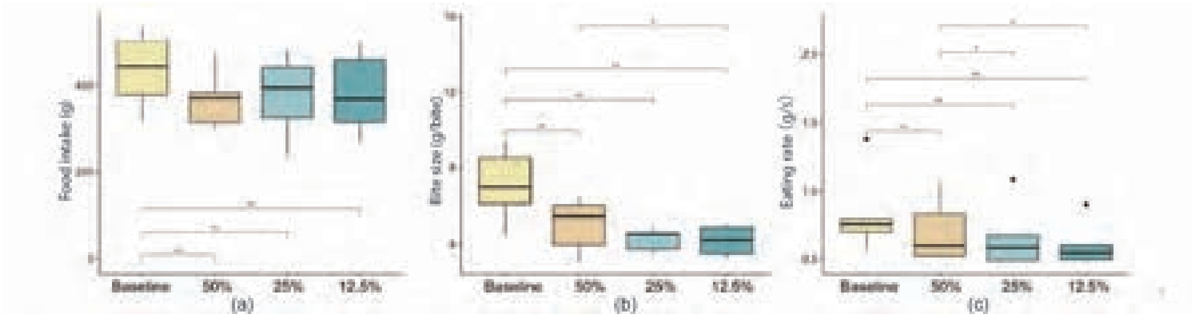

Fig. 10. (a) *food intake*, (b) *bite size*, and (c) *eating rate* for each reduction SPEEDS.

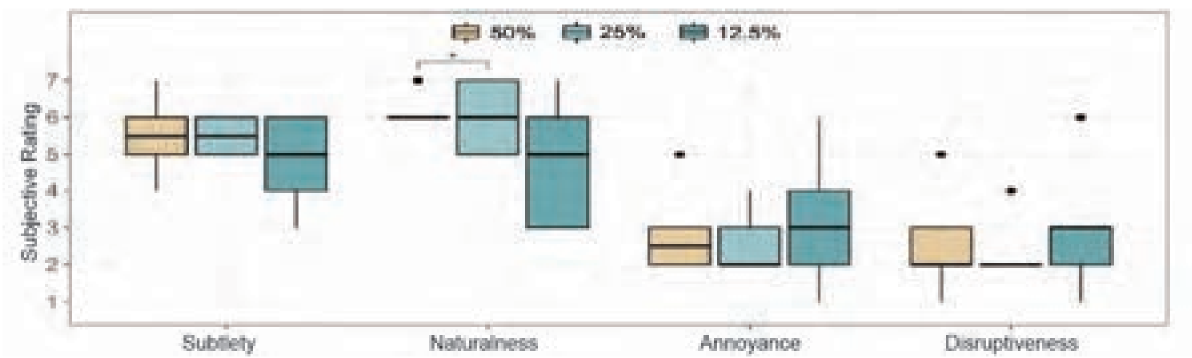

Fig. 11. Subjective ratings for each reduction SPEEDS.

Eating Rate. There was a significant effect of reduction SPEED (χ^2 = 13.5, p < .01) on *eating rate*. Pairwise comparisons indicated that all three reduction speeds could slow down (all p < .01) participants' eating rate as compared to using the baseline speed (0.825 ± 0.265). Additionally, both 25% (0.650 ± 0.210)(p=0.013) and 12.5% (0.597 ± 0.143)(p=0.031) reduction SPEEDS significantly outperformed that of 50% (0.689 ± 0.204).

Appetite Rating. After adjustment for pretest appetite, there was no significant difference between reduction SPEEDS in appetite rating in terms of *hunger*, *fullness*, and *desire to eat*. These results indicated that participants achieved similar satiety across all reduction SPEED conditions.

Subjective Rating. There was a significant effect of reduction SPEED (χ^2 = 7.4, p < .01) on *naturalness* of change. Pairwise comparisons revealed that the reduction SPEED at 50% (median=6) was perceived more naturally (p = 0.01) than that at 25% (median=5). There were no significant differences (all p > .05 on other aspects of user perception (see Fig. 11).

According to these findings, **RQ7** can be answered: all three speeds (i.e., reduction within the first 50%, 25%, and 12.5%) were effective in minimising overall food consumption without interrupting the eating experience, as compared to the BASELINE spoon of 10ml, which was static throughout. Additionally, as compared to the speed at 50%, the "faster" speeds (e.g., 25% and 12.5%) could reduce the eating rate more effectively. To determine the optimal reduction speed that can effectively influence oral processing behaviour while being as subtle as possible, we followed the similar principle used in Study 1. That is, as there are no significant differences between the speed at 25% and 12.5% in terms of oral processing behaviour and user perception, we chose the faster speed at

12.5% for its higher potential of limiting bite size, eating rate, and food intake while minimising disruption in the eating experience.

6.3 Sub-Study 3.3

The results from Sub-Study 3.1 and 3.2 showed that a dynamic *SSpoon* that 1) changes from a normal eating spoon to a small spoon and 2) at a reduction interval of 1ml during the first 25% of food intake can reduce the eating rate and, thus contribute to the reduction in overall food consumption. However, it is unclear whether this shape-changing spoon is as effective at regulating participants' oral processing behaviour as compared to static spoons (i.e., the normal eating spoon and the small spoon) on the users' overall eating experience across people with varying BMIs.

6.3.1 Participants. 16 participants (4 females and 12 males), aged 22 to 25 (M = 23.25, SD = 1.45) with a BMI of 19.2 to 28.7 (M = 24.2, SD = 2.94), of which half of them were overweight were recruited.

6.3.2 Test Spoons. We used three types of spoon: a dynamic *SSpoon*, a static small spoon, and a static normal eating spoon. Similar to Subs-Study 3.1, we customised the reduction speed of dynamic *SSpoon* based on each participant's normal speed of consumption.

6.3.3 Procedure. The study was conducted over three days, at a fixed time slot, with each day focusing on a different spoon condition, similar to Sub-Study 3.2. The only difference was that, during the familiarization trial, participants visually ranked their overall preference for each spoon before using it. After all the experimental sessions, participants were also asked to rank their preferences based on their eating experiences.

6.3.4 Design. We used a mixed design, with SPOON (three levels: dynamic SSPOON, static SMALL SPOON and static NORMAL EATING SPOON) as a within-subject independent variable and BMI (two levels: NORMAL WEIGHT and OVERWEIGHT) as a between-subject independent variable. In terms of dependent variables, we measured oral processing behaviour, user appetite, and subjective feedback in the same way as in Study 2.

6.3.5 Results. The assumption of normality was tested using Shapiro-Wilk ($p > .05$). Either Two-way mixed ANOVA or a global alternative using Anova Type Statistic (ATS - R software nparLD package [72]) (if ANOVA assumptions are violated) was performed on each parameter of oral processing behaviour, appetite ratings and subjective ratings. For post hoc comparison, either Independent-sample t-test or Mann-Whitney U test were conducted for between factors, and either One-way repeated measures ANOVA or Friedman test for within factors were employed with Bonferroni corrections.

In summary, there were significant effects of SPOON on *food intake*, *eating rate*, *bite size rate*, *number of bites*, and *percentage of active consumption* across all BMI, all at the $p < .05$ level. There was also a significant effect ($p < .05$) of BMI on *food intake* and *number of bites*. Below, we present more details on key results that provide insights into our final research question see Figure 12.

Food intake. There was a significant main effect of SPOON ($F_{1.19,16.63} = 25.68$, $p < 0.001$, $\eta^2_G = .04$) and BMI ($F_{1,14} = 6.10$, $p = 0.027$, $\eta^2_G = .29$) on *food intake*. Pairwise comparisons indicated that OVERWEIGHT participants (612 ± 129) consumed more ($p < .000$) than that of NORMAL WEIGHT participants (452 ± 183). While this 35% difference was expected [71], both SMALL SPOON (519 ± 188) and SSPOON (532 ± 155) could reduce the participants' *food intake* more effectively (both $p < .01$) than a NORMAL EATING SPOON (558 ± 161). However, there was no significant difference between the two.

Eating Rate. There was a significant main effect of SPOON ($F_{1.02,14.35} = 32.42$, $p < 0.001$, $\eta^2_G = .11$) on *eating rate*. Pairwise comparisons indicated that both SMALL SPOON (0.98 ± 0.27) and SSPOON (0.99 ± 0.25) can slow down

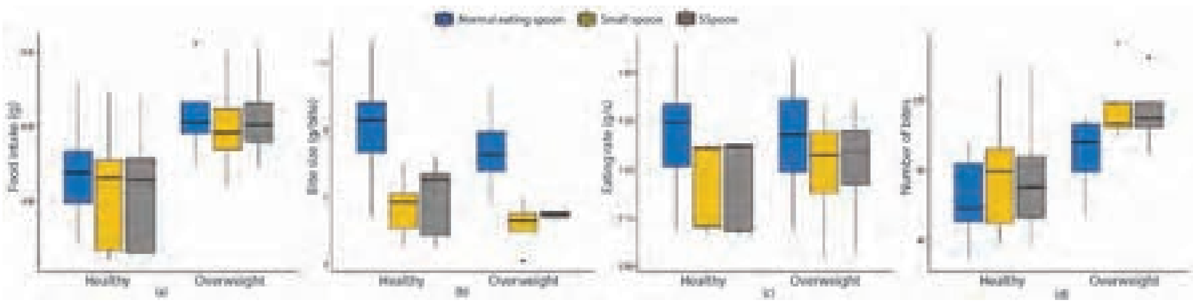

Fig. 12. (a) *Food intake*, (b) *bite size*, (c) *eating rate*, and (d) *number of bites* for each SPOON.

(both $p < .001$) participants' *eating rate* as compared to a NORMAL EATING SPOON (1.18 ± 0.32). However, there was no significant difference between the two.

Bite Size. There was a significant main effect of SPOON ($F_{1.11,15.57} = 43.85$, $p < 0.001$, $\eta^2_G = .52$) on *bite size*. Pairwise comparisons indicated that both SMALL SPOON (5.46 ± 0.84) and SSPOON (5.74 ± 0.81) can reduce (both $p < .001$) participants' *bite size* as compared to a NORMAL EATING SPOON (7.81 ± 1.50). However, there was no significant difference between the two.

Number of Bites. There were significant main effects of SPOON ($F_{1.25,17.56} = 16.65$, $p = 0.001$, $\eta^2_G = .11$) and BMI ($F_{1,14} = 5.43$, $p = 0.035$, $\eta^2_G = .26$) on *number of bites*. Pairwise comparisons indicated that OVERWEIGHT participants (106 ± 24.9) took more *bites* than that of NORMAL WEIGHT (73.2 ± 35.1) ($p < .001$). Additionally, participants using either SMALL SPOON (97.8 ± 36.6) or SSPOON (91 ± 37.9) took more *bites* (all $p < .001$) than while using a NORMAL EATING SPOON (75.9 ± 27.9). However, there was no significant difference between the two.

Appetite Rating. There was no significant difference between SPOONS in *appetite rating* in terms of *hunger*, *fullness*, and *desire to eat* (all $p > .05$). Similar to Sub-Study 3.2, this indicated that all participants achieved similar satiation across the three SPOON conditions.

Subjective Rating. We used Friedman tests and Wilcoxon signed-rank tests with Bonferroni corrections for post hoc comparisons to analyze subjective rating of different spoon based on participants' BMI levels [34].

User perception among normal weight participants. There were significant effects of SPOON on *ease of use* ($\chi^2 = 12.5$, $p = .001$), *comfortable to use* ($\chi^2 = 13.7$, $p < .001$), *natural to use* ($\chi^2 = 12.1$, $p = .002$), and *willingness to use frequently* ($\chi^2 = 13.1$, $p = .001$). Pairwise comparison revealed that participants of normal weight perceived SSPOON as easier, more comfortable, and more natural to use, therefore they were more willing to use it frequently than a static SMALL SPOON (all $p < .04$). Additionally, a static NORMAL EATING SPOON was considered as more comfortable and more willing to be used frequently than a SMALL SPOON (all $p < .03$) (see Fig. 13).

User perception among overweight participants. There was a significant effect of SPOON on *ease of use* ($\chi^2 = 13.1$, $p = .001$), *comfortable to use* ($\chi^2 = 16$, $p < .001$), *natural to use* ($\chi^2 = 13$, $p = .002$), and *willingness to use frequently* ($\chi^2 = 15.2$, $p < .001$). Pairwise comparison revealed that overweight participants perceived both SSPOON and the static NORMAL EATING SPOON as easier, more comfortable, and more natural to use, therefore they were more willing to use it frequently than a static SMALL SPOON (all $p < .04$). There was no significant difference between SSPOON and NORMAL EATING SPOON in terms of ease of use, naturalness to use, and willingness to use it frequently (all $p < .04$). However, participants who were overweight perceived using NORMAL EATING SPOON (median=5.5) as more comfortable ($p = .031$) than using SSPOON (median=4.5) (see Fig. 13).

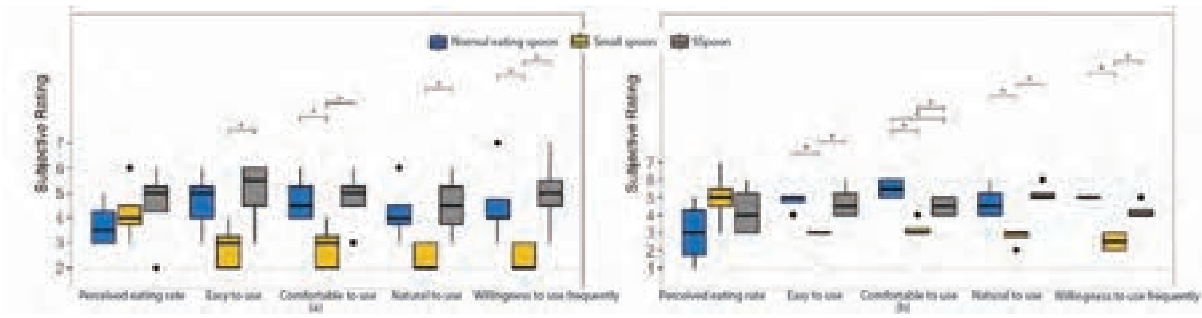

Fig. 13. Subjective ratings between the NORMAL EATING SPOON, SMALL SPOON, and SSPOON among participants ((a).NORMAL WEIGHT (b). OVERWEIGHT).

In terms of visual appearance ranking, SSPOON and NORMAL EATING SPOON are the top two choices, with 6 (66.6% were overweight) of 16 participants preferring SSPOON over NORMAL EATING SPOON. When they were asked to rank between SSPOON and NORMAL EATING SPOON, participants randomly selected one of them as they perceived the difference to be indiscernible. This was reflected in the result that half of the participants preferred SSPOON over the NORMAL EATING SPOON. This result is consistent with that of Study 2: SSPOON was capable of achieving similar user satisfaction as compared to a regular spoon.

As expected, participants unanimously ranked a static SMALL SPOON as the least desirable one due to the fact that it is "flat and shallow" (P2) and causing them to eat less amount for the same bite in the SSpoon and normal eating spoon. As a result, they ended up scooping more times which was perceived as “less efficient and unsatisfying” (P14). All participants disliked using the SMALL SPOON because it was “less useful, especially for drinking soup”.

Based on these aforementioned findings, **RQ8** can be answered. For both normal weight and overweight participants, dynamic *SSpoon* could be as effective as static small spoon in limiting bite sizes, eating rates, and consequently reducing over consumption of food than a normal eating spoon. Additionally, due to its gradual and subtle shape change, dynamic *SSpoon* could relieve the initial reluctance and practical challenges associated with using a small spoon, resulting in a similar level of overall dining satisfaction.

7 OVERALL DISCUSSION

7.1 Shape-changing Effects on Eating Behaviour and User’s Perception

Our studies revealed that *SSpoon* has significant advantages in regulating eating behaviour for both normal weight and obese participants over a classic static spoon. *SSpoon* can achieve comparable effects to a small spoon in reducing food intake while retaining similar user satisfaction to a large spoon. While the benefits of food intake regulation can be easily achieved by adopting a small spoon [44], it faces significant usage barriers. This is because our participants found using it to be "abnormal" (P2 in Sub-Study 3.3), "not in accordance with the dining norm" (P6 in Sub-Study 3.3), and especially challenging for liquid food, thus negatively affecting the overall eating experience. In fact, all participants in Study 3 ranked small spoon to be the least preferred, suggesting that users would not spontaneously use a small spoon even if they had a choice. Therefore, we believe that simply advocating the use of small spoons for regulating food intake is likely to achieve limited success. By introducing the right shape-changing mechanism, we could alleviate the initial negative perception associated with using small spoon, yet achieve similar food regulation effects. While our normal weight participants preferred normal eating spoon and *SSpoon* equally, we see great potential in introducing *SSpoon* to people who are overweight. Our

Study 3 found that they perceived *SSpoon* as satisfying as normal eating spoon, except in terms of comfort. This is because, as the spoon gradually reduced its size, they had to scoop more frequently to achieve their desired amount of food, thus requiring more effort.

In investigating how participants perceived *SSpoon*, we found that their eating habits, especially how they consumed liquid, affected their perception and interpretation. The reason is that solid foods like rice tend to stick together, so the depth of the spoon did not impact as much on the amount of food scooped, which was consistent with our previous studies (Study 1 and 2). Moreover, due to its gradual and subtle changing properties, none of the participants in our Study 3 noticed that the spoon was changing as they consumed rice. The change was only noticeable when soup (liquid food) was consumed and how participants consumed it. Some participants consumed soup only at the end of the meal (after rice had been consumed), while some interleaved the consumption of soup with that of rice throughout the meal.

Here, we present two theoretical explanations derived from cognitive science and social psychology for interpreting the observed impact of *SSpoon*'s shape-changing features on user perception.

7.1.1 Perceptual Visual Bias Could Drive Reward Satisfaction Effects. Participants who consumed the liquid food at the end of the meal were not aware that *SSpoon* size had changed over time. Interestingly, they perceived that they could drink more as compared to using a small spoon, even though *SSpoon* size had already been changed to that of a small spoon at that time. This finding indicates that the estimation of food intake is largely biased by the initial visual assessment of the spoon size and that the larger initial size deceives users into believing that they are eating more. This finding is also consistent with previous studies in psychology and cognitive neuroscience, which have found that humans cannot accurately estimate the volume of food consumed. They relied on alternative contextual and environmental cues, such as the size of the bowl and cutlery [97], to help with their estimation. Thus, shape-changing spoons can be used to create the illusion of eating more without imposing additional burdens on their stomach.

The reason in which *SSpoon* creates a similar satisfaction value to a normal-sized spoon can also be explained using the reward satisfaction theory [68]. We all know that rewards satisfaction in humans is not linear. Often, the first reward creates the highest satisfaction, and the subsequent rewards' satisfaction decreases over time. *SSpoon* is designed to take advantage of this phenomenon: it uses the normal size in the beginning to preserve the satisfaction generated by the first few bites; and as the reward value of food intake decreases, *SSpoon* reduces its size to exploit users' decreased desire of having large bites. Also, the change benefits from the cumulative satiation of the eating process. By carefully matching spoon sizes with the reward value of the food over time, *SSpoon* regulates users' eating behaviour without introducing dissatisfaction, as demonstrated in our studies.

7.1.2 Confirmation Bias Could Induce the Perception of Satiety. Another psychological theory that can help to explain why decreased food intake does not affect users' satisfaction is the confirmation bias theory [70]. According to this theory, people tend to rationalize things based on their prior beliefs while ignoring evidence that supports an alternative view. In our study, we observed that while some users noticed that they got less and less soup in each scoop throughout the meal, they attributed the reason to themselves being full, thus subconsciously scooping less and less soup. As P8 explained, "I used the spoon [*SSpoon*] at the very beginning for drinking soup; it is easy and satisfying. In the end, I did notice that I could only drink less as compared to the beginning, which I thought it was because I was full." There was no blame placed on the *SSpoon* because the participants were unaware of its ability to change shape automatically. As an alternative, they attributed the less food served to themselves being full, which was in line with their past experience.

7.2 Shape-changing Strategies

7.2.1 Reduction Speeds. We adopted the rate of 1ml after each bite (after the spoon has left the mouth) based on our Sub-Study 3.1 result. Yet, we suggested that different reduction intervals and speed patterns can be further explored. That is, instead of changing the normal eating spoon (10ml) to a small spoon (5ml) using a **constant rate** (e.g., 1ml each time), a **decelerated rate** (e.g., 2ml,2ml,1ml) may also be considered. This is especially important for *SSpoon* reduction speed to match that of individual behaviour and attitude towards food consumption so as to balance between eating regulation and user satisfaction.

7.2.2 Reduction Triggers. In Study 3, we developed a shape-changing strategy based on cumulative food intake. However, one can imagine a more sophisticated shape changing mechanism that adapts to users' real-time eating behaviour and nutrition content. For instance, a real-time eating monitoring system could regulate users' eating rate more actively. Only if rapid eating or consumption of high-calorie food is detected, *SSpoon* needs to intervene by gradually and subtly reducing its volume to adjust/correct the eating behaviour without users' cognitive and behavioural efforts. By incorporating the eating rate detection into the shape-changing strategy, a more flexible and effective intervention could be designed.

7.3 Extending SSpoon

As an emerging field on Tangible User Interfaces, shape-changing interfaces enable objects to physically reconfigure their external geometry to convey information [52, 88], influence behaviour change [91], and deliver dynamic affordances [25, 88]. In this paper, we present a new type of interactive possibility by introducing shape-changing features into the eating context and by designing an adaptive eating tool that could trigger eating behaviour improvements.

7.3.1 To Different Dietary Purposes. Although our primary idea is to help people slow down their eating rate to combat overweight and obesity, the inverse idea of increasing eating rate and thereby increasing energy intake could also be desirable. For instance, in the case of people who are malnourished or elderly who suffer from frailty, *SSpoon* could subtly increase its size over time to encourage the consumption of nutritional food (e.g. vegetables), thus achieving a healthier outcome. More generally, *SSpoon* could offer a versatile solution to promote healthy dietary habits. By dynamically adapting to the eating behaviour we want to encourage or discourage, a new opportunity for tangible interface in the eating context can be achieved.

7.3.2 To Different Tableware. A small change in the eating environment, for instance, alterations in container size [40, 62], utensils size [58], and visual cues about the amount consumed [95, 99] can influence food consumption. For instance, researchers found that a large plate could induce an underestimation of food size, thus leading to overconsumption [96]. Insights from designing *SSpoon* can leverage these findings to achieve a new type of dynamic yet subtle eating behaviour intervention. For instance, a shape-changing plate (SPlate) can be designed to shrink its size to create the illusion that the food is more abundant, therefore maintaining user satisfaction [96] . A shape-changing straw (SStraw) could also be designed to change its hole diameter depending on the drinking behaviour we want to facilitate (e.g., slow down the drinking rate for hot tea). By integrating the shape-changing interface into different tableware, a more dynamic human-food interaction can be achieved.

8 LIMITATIONS & FUTURE WORK

In the above studies, the detection based on food form (in Study 2) and cumulative food intake (in Study 3) is based on the Wizard-of-Oz approach. Despite its ability to demonstrate the potential of our concept, it may not reveal certain technical challenges in implementing the device, which may hinder the practical adoption of *SSpoon* in real-life settings. However, as the advanced technology in shape change [45, 67] and food detection and recognition [104] mature, such effects could be largely relieved.

Food consumption today has become more than an activity for survival; eating has also served as a communicative and social function [38, 65]. As a result, eating behaviour is profoundly affected not only by ingrained eating habits [59] but also by external factors such as social communication [42] and eating environment [16, 64]. Although our proposed solution could make it easier to be adopted in daily eating as compared to prior eating interventions that rely on external devices and user motivation [37], the efficacy of *SSpoon* in real-life settings has yet to be ascertained. More importantly, eating behavioural change and weight management cannot be achieved overnight. Despite the fact that our proposed prototype could be effective in reducing food consumption without affecting the appetite rating, it is worthwhile to examine whether a more continuous reduction in energy intake could cumulatively reduce their body weight and thus help combat overweight and obesity on a long-term basis. Moreover, we are also interested in whether *SSpoon* could train people to take smaller portions over time, so that the sustained effects would persist even after the intervention is removed.

Furthermore, even though our results are significant among both normal weight and overweight users, the present study relies on a moderate sample size and a small variation in the demographic characteristics of the participants. Considering the difference in eating rate that was found in terms of age [47, 48], gender [47, 48, 77], ethnicity [48], and BMI [74] the current study limits itself to examining the extent to which the use of *SSpoon* can affect these differences. Future replication studies could help generalize current research findings to a broader population.

9 CONCLUSION

In this work, we designed, developed, and examined a shape-changing spoon (*SSpoon*) that could subtly modify its food-carrying volume to slow down the eating rate without sacrificing eating pleasure in standardized meal settings. Our first study provided empirical evidence that changing the depth of spoons (i.e. Z dimension) not only limits the bite size, but also maintains their usability. The study additionally found that there was an optimal range for transformations for different food forms. By leveraging these results, we iteratively developed the *SSpoon* prototype through a series of design explorations. In order to validate the effect of *SSpoon* on eating rates, appetites, and eating experiences, we introduced two shape-changing mechanisms: instant transformations based on food form (Study 2) and subtle transformations based on cumulative food intake (Study 3). Our results demonstrated that, by using *SSpoon*, participants were able to reduce their bite size and eating rate; thus contributing to a reduction in food consumption as compared to using a static normal eating spoon. By incorporating the shape-changing feature into the spoon, it could also alleviate the initial reluctance associated with using a static small spoon, thus retaining the eating experience. Although our study was performed under ideal simulated conditions, we consider it as a first step toward exploring the feasibility of implementing a shape-changing spoon, and future developments (e.g. automatic food form detection and more seamless shape-changing technology) will be needed to realise its full potential. Furthermore, we discussed insights for the future design of shape-changing strategies and the potential application of such technologies to achieve optimised eating behaviour.

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A SUPPLEMENTAL MATERIALS

A.1 Pairwise comparisons between each spoon SIZE on each food TEXTURE.

Bite size_solid

	3	5	7	9	11	13	15
3							
5	**0.146**						
7	**	*					
9	****	**	**0.297**				
11	****	**	**0.119**	**0.702**			
13	***	**	**0.209**	**0.818**	**0.876**		
15	**0.218**	**0.097**	**0.936**	**0.459**	**0.206**	**0.155**	

Usability_solid

	3	5	7	9	11	13	15
3							
5	*						
7	**0.1**	**0.864**					
9	**0.706**	**0.743**	**0.1**				
11	**0.422**	**	*	**			
13	**	****	****	****	**0.073**		
15	****	***	***	****	****	****	

Bite size_semi-solid

	3	5	7	9	11	13	15
3							
5	*						
7	****	*					
9	****	**	**0.275**				
11	****	***	**0.382**	**0.1**			
13	***	*	**0.059**	**0.246**	**0.7**		
15	****	*	**0.607**	**0.052**	**0.206**	**0.461**	

Usability_semi-solid

	3	5	7	9	11	13	15
3							
5	**0.352**						
7	**0.823**	**0.147**					
9	**0.051**	**0.075**	**0.512**				
11	****	****	****	****			
13	****	****	****	****	**		
15	****	****	****	****	****	*	

Bite size_liquid

	3	5	7	9	11	13	15
3							
5	****						
7	****	****					
9	****	****	****				
11	****	****	****	***			
13	****	****	****	****	***		
15	****	****	****	****	****	*	

Usability_liquid

	3	5	7	9	11	13	15
3							
5	****						
7	****	**					
9	****	****	*				
11	****	***	**0.085**	**0.105**			
13	****	***	**0.072**	**0.345**	**0.674**		
15	****	*	**0.721**	**0.334**	**0.098**	**0.091**	

A.2 Subjective ratings between the BASELINE spoon (top) and SSPOON IN STUDY 2 (bottom).