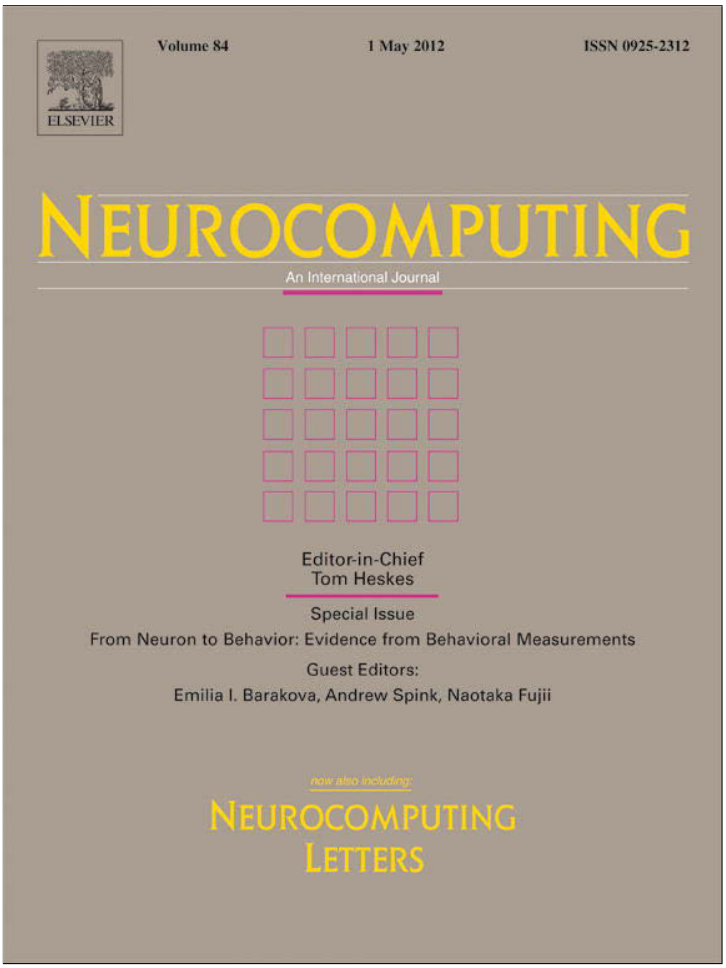

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Food intake and chewing in women

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ABSTRACT

The frequency and weight of food removed from a plate and placed in the mouth was recorded by computer and synchronized with the pattern of chewing recorded by video filming of the maxillary–mandibular region in women selected for eating with a decelerating speed (decelerated eaters) or a nearly constant speed (linear eaters). Because linear eaters are at risk of developing disorders of food intake, body weight and mood, detailed study of eating behavior is clinically important. Although the pattern of chewing was similar in both groups, the decelerated eaters took fewer mouthfuls, which weighed less, by the end of the meal. Linear eaters ate the same amount of food throughout the meal. The rate of chewing a piece of chewing gum was lower than the rate of chewing food in both groups and lower in linear eaters than in decelerated eaters. The chewing gum chewing frequency correlated with the initial speed of eating food, which was lower in linear than in decelerated eaters. The neural network of chewing is well studied, engaging dorsal raphe serotonin neurons which project to orbito- and prefrontal cortex, whose activity, if experimentally changed, produces change in mood which mimic those produced by changes in chewing and parallel the changes in mood of patients with eating disorders. This detailed behavioral description of women at risk of developing disordered eating is the first step for integrating brain function and ingestive behavior in both healthy women and patients.

1. Introduction

Human food intake has been modeled by a curve of cumulative intake; $y=kx^2+lx$, where y is food intake, x is time, the k-coefficient is the change in the speed of eating over the course of the meal and the l-coefficient is the initial speed of eating [1–7]. It has been reported that $k>0$ in individual bulimic women [6,8], but in most cases $k<0$ [3–7,9]. However, in many studies, the values of the k- and l-coefficient are not reported [10].

To obtain data for the curve of cumulative food intake, subjects eat from a plate placed on a scale that is connected to a computer, which records the weight loss of the plate as the subjects eat [4,7,11]. Mandometer®, a development of this method, provides feedback on how to eat on a screen during the meal, allowing experimental variation in the speed of eating and in the amount to be eaten [7], a feature that is used in normalizing eating behavior in clinical populations [12,13]. During control meals, women eating with a decelerating ($k<0$), or constant speed ($k\approx 0$), consume similar amounts of food [5–7]. Westerterp-Plantenga et al. [5,6] referred to these two groups as decelerated and linear eaters; however, some women fall in between these categories. Although the sensory characteristics of the food [1] and cognitive processes [5] have been thought to play a role, the parameters of the cumulative intake curve cannot be clearly related to biological factors (see discussion in [1,14]).

Linear eaters, unlike decelerated ones, had difficulty maintaining their level of ingestion when the speed of eating was experimentally changed via feedback on the Mandometer® screen [7]. They ate less food when eating at a decreased speed and their curve of cumulative food intake became similar to that of anorexic patients [7,15], and when the speed of eating was experimentally increased, their curve of cumulative food intake became similar to that of obese patients [15]. Interestingly, linear eaters estimated their feeling of fullness as high as anorexic patients when eating at a decreased speed, despite eating less food. Conversely, they estimated their feeling of fullness as low as obese patients when eating at an increased speed, despite eating more food [15]. These results support the hypothesis that eating with a nearly constant speed is a behavioral risk factor for long term loss of control over eating and consequently loss of control over body weight.

The mechanics of chewing in humans have been studied meticulously [16–19]. While the pattern of chewing depends on the characteristics of the food and varies among individuals [20],

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the frequency of the chewing rhythm is relatively stable [16]. Recently, we proposed a neurobiological model, predicting that abnormal chewing is the mediator of the disturbed psychology in eating disorders [21]. However, limited information is available on the characteristics of chewing during meals under normal circumstances [22], and linear and decelerated eaters have not been studied.

The curve of cumulative food intake is a measure of the weight of the food which is removed from a plate over the course of the meal, i.e., a measure of the frequency at which the food is consumed. The actual pattern of chewing in relation to the spacing of mouthfuls (also referred to as bites) has not been extensively analyzed. Attempts at such an analysis have used food items of variable size and weight [23], and semi-liquid, chocolate-based drinks [24]. With smaller pieces of food, subjects chewed for a longer period of time and at an increased frequency, but the duration of the pauses between mouthfuls and the amount of food consumed were not affected [23]. By contrast, with semi-liquid meals, smaller mouthfuls and longer intra-oral processing time reduced the amount consumed [24].

In order to study chewing and cumulative intake of food, we used video recording of the maxillary–mandibular region in combination with computer recording of the removal of food from a plate [25]. With this method, eating behavior emerged as bursts of chewing followed by pauses, a pattern which remained relatively stable over the course of the meal in women with curves of cumulative food intake with k-values between decelerated and linear eaters (-0.25 on average [19]). In the present study, we used this method to determine possible differences in chewing and food intake among decelerated and linear eaters. Also, we video filmed the maxillary-mandibular region of decelerated and linear eaters chewing a piece of chewing gum in order to study chewing in the absence of feedback from ingested food.

2. Materials and methods

2.1. Subjects

Fifty-two women were recruited from a nearby university campus by an advertisement. They were healthy, had no history of anxiety or eating disorders and they ate regular food. They were between 18 and 25 years old and their body mass index (BMI, weight/height squared, kg/m^2) was between 18 and 25. The women were divided into two groups of decelerated eaters and two groups of linear eaters; 13 women were excluded because their curve of cumulative food intake had a rate of deceleration $-0.2 < k < -0.3$.

The first group of decelerated eaters ($n=9$) was 24.2 (20.7–24.8) years old (median; range) and their BMI was 21.5 (20.6–24.5) and the first group of linear eaters ($n=9$) was 23.9 (20.2–25) years old and their BMI was 21.1 (19.5–24.2). The second group of decelerated eaters ($n=10$) was 23.6 (19.6–24.6) years old and their BMI was 20.9 (18.5–24.5) and the second group of linear eaters ($n=11$) was 22.8 (19.5–24.3) years old and their BMI was 21.4 (19.9–23.7). The differences between the groups are not statistically significant.

We study women because our aim is to understand eating disorders, which mainly affect women.

2.2. Apparatus

Mandometer® (Mikrodidakt, Lund, Sweden) consists of a scale connected to a custom made computer which reads the weight of a plate placed on the scale every second during the meal. Mandometer® expands on the capabilities of similar devices [4,11,26] by making it possible to experimentally change the speed of eating through feedback on the pattern of eating via a 15″ TFT touch screen. Two digital video cameras (DigitalCam, Samsung, Seoul, South Korea), placed about 2.5 m from the eating table were also used.

2.3. Procedure

2.3.1. General procedures

The women were first informed about the study in an introductory meeting. They then had three lunches using Mandometer®, separated by less than a week. In the first, they were made familiar with the test procedure and no data were collected. During the three test days, the women agreed to have an individually prearranged breakfast, based on their habits (as described during the introductory meeting), at 08:00 am. Breakfasts remained identical across the test meals and the women agreed to refrain from drinking anything but water before the meal, served between 11:30 am and 1:00 pm. They could eat as much as they wanted by serving themselves from a plate with 1.5–2 kg food placed on a tray on an adjacent table, available throughout the meal. There were no constraints during the meal, no instructions about e.g., mouthfuls were provided. At the beginning of the test meal, the temperature of the food was about 50 °C. All meals were taken individually, in a room separated from external influences, with no windows and with lighting conditions optimized for video recording. Before each test, the women rated their satiety, mood, anxiety and quality of the foods using custom made questionnaires with visual analog scales. These questionnaires were used to detect variations in emotional status and in food attitudes. After the meal the satiety level was evaluated again. No woman was excluded on the basis of her responses to the questionnaires.

2.3.2. Eating behavior

The first groups of decelerated and linear eaters were served chicken and pieces of vegetables (426 kJ, 10.7 g protein, 8 g carbohydrate and 2.5 g fat/100 g, Findus AB, Bjuv, Sweden). This food will be referred to as test food I. These women were videotaped during the two test meals, one camera was directed towards the maxillary–mandibular region of the woman and the other was directed towards the plate on the scale of the Mandometer®.

2.3.3. Chewing gum

The other groups of decelerated and linear eaters were served curry rise and chicken pieces (400 kJ, 4.5 g protein, 15 g carbohydrate and 18 g fat/100 g, Findus AB, Bjuv, Sweden). This food will be referred to as test food II and is only slightly different from test food I. The women were not video filmed during these tests but their maxillary–mandibular region was video filmed for 5 min in two separate tests while the women were chewing one piece of chewing gum with a peppermint flavor (Wrigley Scandinavia AB, Stockholm, Sweden). Two tests with chewing gum were performed at the same time of day as the test meals.

These procedures were approved by the Regional Central Ethical Review Board in Stockholm.

2.4. Data collection and analysis

Data on the weight-loss of the plate during the meal were collected and stored by the Mandometer® and transferred to a PC for analysis.

Data on mouthfuls, i.e., food removed from the plate and placed in the mouth, and data on chewing, i.e., obvious

occurrences of complete chewing cycles (opening and closing of the maxillary–mandibular area), were obtained from the two video cameras and transferred to a PC for analysis (see [25] for details). This method has been validated against electromyographic recording of chewing [25].

The combined analysis of cumulative food intake using Mandometer® and chewing using video recording of the maxillary–mandibular region has been described before [25]. In brief, mouthful data are synchronized with the pattern of chewing, while errors are corrected automatically. A mouthful consists of putting food on a fork and loading the food into the mouth. This is followed by an uninterrupted burst of chews lasting about 8 s followed by a pause lasting about 4 s; occasionally, chewing can be observed during the pause (in less than 5% of the mouthfuls) [25]. The following measures are generated: food intake (g), rate of deceleration (k-coefficient), initial speed of eating (l-coefficient), duration of the meal (min), number and weight of mouthfuls, durations of bursts of chewing and pauses, number of chews/s and the distribution or chews within bursts.

Because the women were selected as decelerated and linear eaters, the characteristics of their cumulative food intake were not evaluated statistically.

Each meal was divided temporally into thirds. Because of the expected inter-individual variability in the behavioral measures [7,15,25], the results are reported as box plots, i.e., 5, 25, 50, 75 and 95 percentiles in the graphs. The frequency of chewing between individuals is less variable [16,21,25] and the distribution of chewing over the course of the meal is reported as mean (SD). Each burst was divided into quartiles and the number of chews was expressed as percentage of the total number of chews within each quartile of the burst. This measure was then used to compare the distribution of chews in each third of the meal. The results from chewing a piece of chewing gum are reported as means (SD). Pauses of 2 s or more, noted in 501 out of 25301 pauses (1.98%) recorded in these tests, were caused by the subjects moving physically and were therefore excluded. Changes in the outcome measures over time were analyzed by ANOVA for repeated measures followed by Tukey's HSD post hoc tests (Statistica 9.1. Statsoft, Tulsa, Oklahoma, USA).

When differences between groups were statistically insignificant the outcome in the groups will be referred to as "similar".

3. Results

3.1. Cumulative food intake and satiety

The curve of cumulative food intake was similar in the two groups of decelerated eaters and the two groups of linear eaters and comparable to those of our previous study (Fig. 1) [7]. However, whereas the prolongation of the meal among linear eaters was not statistically significant in that study, it was significant in the present study [test food I: $t(16)=-2.6$, $p=0.017$] and test food II [$t(19)=-2.4$, $p=0.037$].

The estimation of satiety among decelerated and linear eaters was also similar to our previous report [7]; with a comparable increase after the meal in all groups (Table 1).

3.2. Eating behavior

3.2.1. Mouthfuls

There was no effect of group [$F(1,16)=3.213$, ns], a significant effect of time [$F(2,32)=6.487$, $p=0.04$] and a significant group × time interaction [$F(2,32)=3.944$, $p=0.029$] on the number of mouthfuls over the course of the meal (Fig. 2A). Decelerated eaters took fewer mouthfuls during the last third of the meal than during the first [$p=0.012$] but there was no time dependent effect among the linear eaters (Fig. 2A).

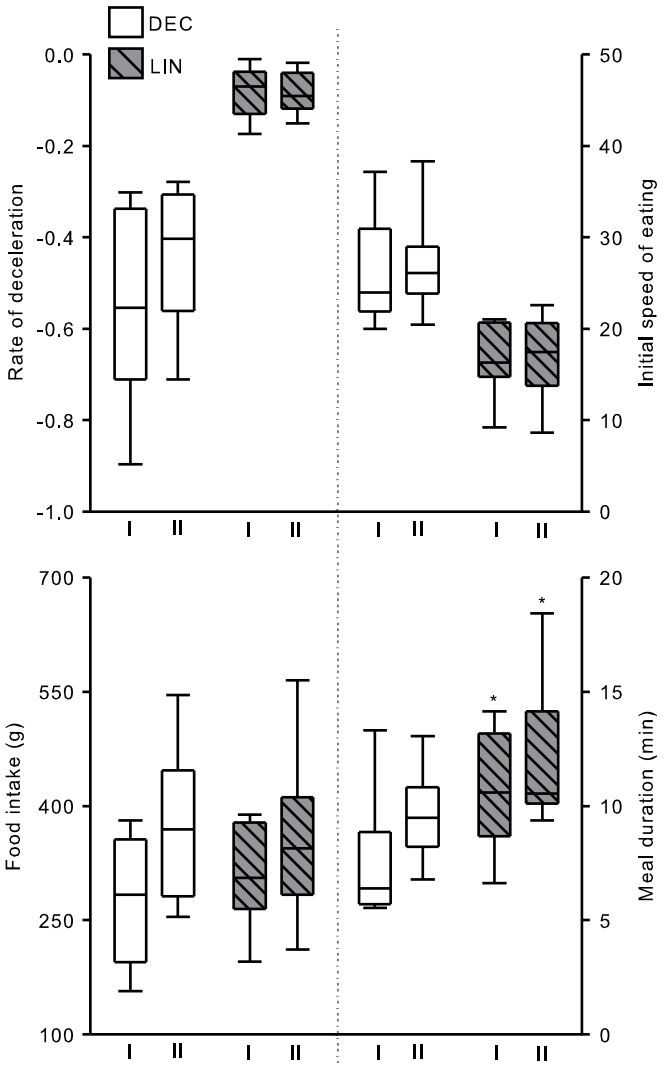

Fig. 1. Rate of deceleration (k), initial speed of eating (l), food intake (y) and duration of the meal in the curve of cumulative food intake; $y=kx^2+lx$ of women selected for $k<-0.3$ (decelerated eaters, DEC) or $k>-0.2$ (linear eaters, LIN). The two groups of DEC and LIN eaters ate slightly different test foods (I and II). Data are expressed as box plots, i.e., the 5, 25, 50, 75 and 95 percentile. There were 9–11 women per group. $^*p<0.05$ compared to the respective DEC group.

Table 1
Estimation of satiety in women selected for eating at a decelerating speed (decelerated eaters, DEC) or at a nearly constant speed (linear eaters, LIN). The women ate slightly different foods (I and II). There were 9–11 women per groups and values are mean (SD). $^*p<0.05$ compared to satiety measurement before the meal.

Group	Before meal	After meal
DEC I	17.8 (15.1)	92.3* (8.2)
LIN I	22.5 (16.1)	90.9* (4.4)
DEC II	23.2 (12.1)	91.6* (6.9)
LIN II	12.8 (8.9)	96.1* (4.2)

3.2.2. Mouthful weight

There was no effect of group [$F(1,16)=1.704$, ns], a significant effect of time [$F(2,32)=11.008$, $p<0.001$] and a significant group × time interaction [$F(2,32)=4.317$, $p=0.022$] on the weight

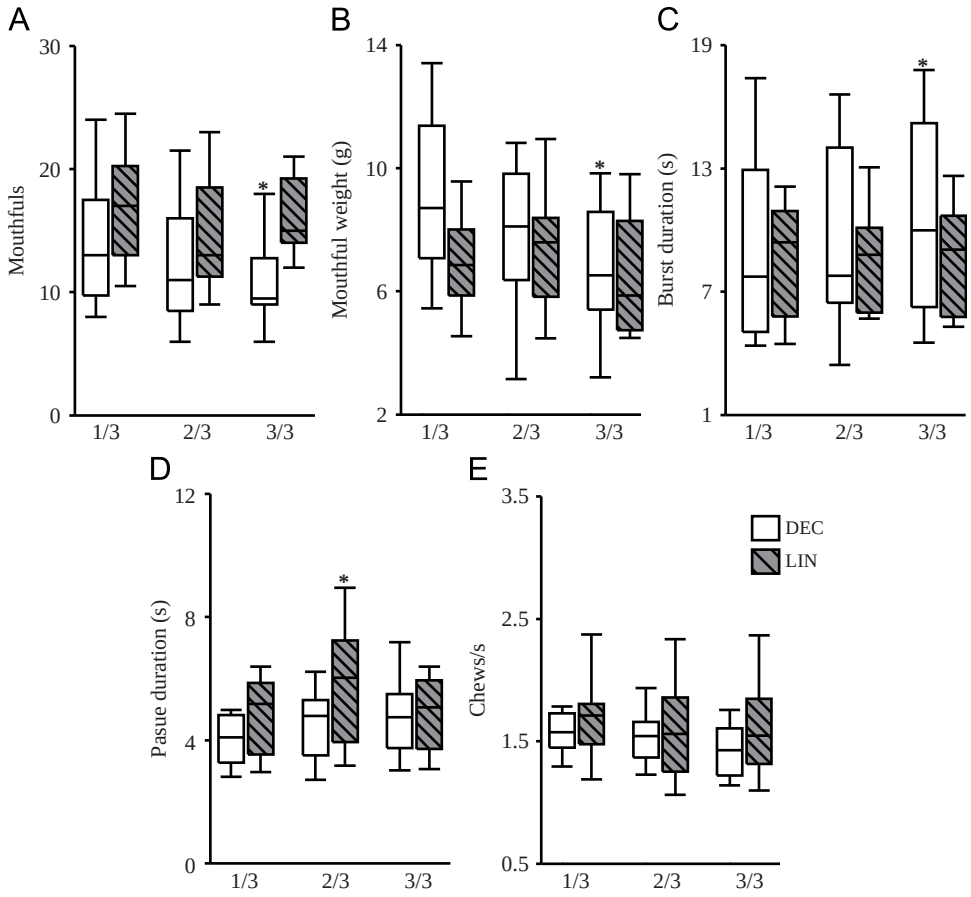

Fig. 2. Number of mouthfuls (A), weight of mouthfuls (B), duration of bursts of chewing (C), duration of pauses between mouthfuls (D) and chews per second (E) in each third (1/3, 2/3 and 3/3) of meals eaten by women selected for eating at a decelerating speed (decelerated eaters, DEC, $n=9$) or at a nearly constant speed (linear eaters, LIN, $n=9$). Data are expressed as box plots, i.e., the 5, 25, 50, 75 and 95 percentile. $^{*}p<0.05$ compared to 1/3.

of the mouthfuls over the course of the meal (Fig. 2B). The weight of the mouthfuls decreased over the course of the meal among the decelerated the eaters (first vs. last third [$p<0.001$]), but not among the linear eaters (Fig. 2B).

3.2.3. Burst duration

While there was no effect of group [$F(1,16)=0.573$, *ns*], there was a significant effect of time [$F(2,32)=4.947$, $p=0.013$] and a significant group x time interaction [$F(2,32)=6.715$, $p=0.004$] on the duration of the bursts of chewing (Fig. 2C). There were no significant between group effects, but the decelerated eaters had significantly longer bursts of chewing during the last third of the meal compared to the first [$p=0.007$] (Fig. 2C).

3.2.4. Pause duration

There was no effect of group [$F(1,16)=1.456$, *ns*], but there was a significant effect of time [$F(2,32)=4.813$, $p=0.015$] on the duration of pauses between mouthfuls. The group × time interaction was not significant [$F(2,32)=3.143$, *ns*]. Linear eaters had significantly longer pauses during the second third of the meal compared to the first [$p<0.05$] (Fig. 2D), but because this increase occurred in the middle third of the meal without relationship to any other measure, it was probably an artifact and will not be considered further.

3.2.5. Chews/s

There was no effect of group [$F(1,16)=0.802$, *ns*] or time [$F(2,32)=1.904$, *ns*] and no time × group interaction [$F(2,32)=1.936$, *ns*] on the chewing frequency during chewing bursts across the meals (Fig. 2E).

Neither the rate of deceleration nor the initial speed of eating correlated with the in-meal chewing frequency among decelerated or linear eaters (data not shown).

3.2.6. Distribution of chews within bursts

There was no effect of time [$F(2,24)=1.233$, *ns*] but there was a significant effect of quartile [$F(3,72)=72.26$, $p<0.001$] on the distribution of chews within bursts for decelerated eaters. The time x quartile interaction was not significant [$F(6,72)=0.158$, *ns*]. The results for the linear eaters were similar; no effect of time [$F(2,24)=0.436$, *ns*], a significant effect of quartile [$F(3,72)=37.16$, $p<0.001$] but no time × burst quartile interaction [$F(6,72)=0.309$, *ns*].

In both decelerated and linear eaters there was a significant increase of chews in the second and fourth quartiles of the bursts across the meal [$p<0.001$ in all cases] (Fig. 3).

3.3. Chewing a piece of chewing gum

Decelerated eaters chewed a piece of chewing gum at a higher frequency (1.24 (0.22)) chews/s than linear eaters (1.03 (0.21)) chews/s [$t(19)=2.144$, $p=0.045$]. These frequencies were significantly lower than the average frequency observed when the decelerated eaters [$t(17)=-2.894$, $p=0.01$] as well as the linear eaters ate food [$t(18)=-4.602$, $p<0.001$] (Fig. 2E).

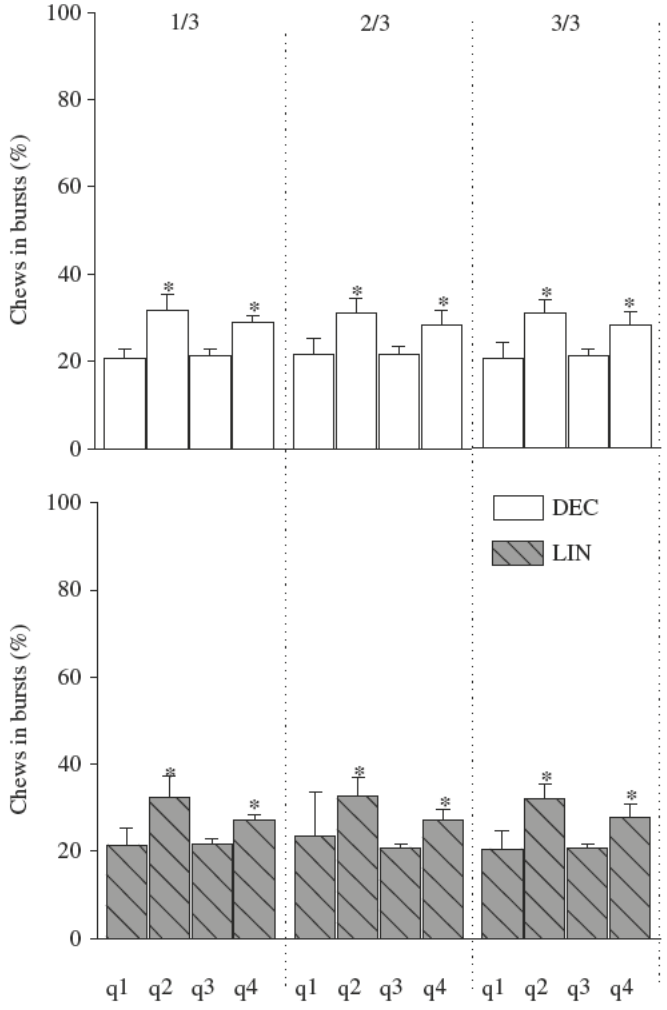

Fig. 3. Distribution of chews within bursts of chewing in each third (1/3, 2/3, 3/3) of meals eaten by women selected for eating at a decelerating speed (decelerated eaters, DEC, $n=9$) or at a nearly constant speed (linear eaters, LIN, $n=9$). The chews are expressed as percentage (SD) within quartiles (q1, q2, q3 and q4) of the total number of chews within bursts. $^{*}p<0.05$ compared to q1.

The rate of chewing a piece of chewing gum correlated with the initial speed of eating during food intake [combined decelerated and linear eaters: $r=0.632$, $p=0.02$] (Fig. 4).

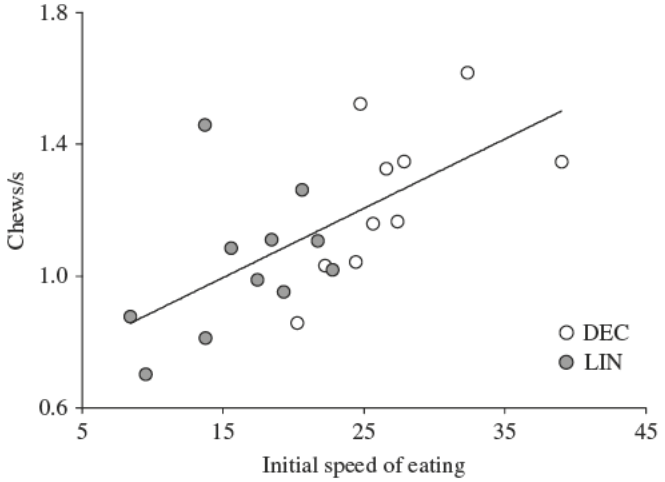

Fig. 4. Correlation between the frequency of chewing a piece of chewing gum for 5 min (chews/s) and the initial speed of eating food in women selected for eating at a decelerating speed (decelerated eaters, DEC, $n=10$) or at a nearly constant speed (linear eaters, LIN, $n=11$).

4. Discussion

A detailed description of food intake is important because firstly, the curve of cumulative food intake is markedly different in both under- and overweight patients compared with normal weight controls [15]. And secondly, display of the normal pattern of eating on a computer screen can be used as real-time feedback to normalize food intake and therefore normalize body weight in both groups of patients [12,13]. A detailed study of chewing is also important because chewing influences a range of cognitive and emotional functions, which have changed in the same patient groups (reviewed in ref [21]). While both cumulative food intake [4–7,11] and chewing have been studied before, the two have never been combined and in studies on chewing the different phases of the meal were not dissociated [22], while some studies employed invasive techniques and unnatural foods [9,23,27,28]. The aim of the present study, therefore, was to describe food intake and chewing over the course of a normal meal.

In a pioneering, detailed study, Westerterp-Plantenga et al. [5] introduced the nomenclature of "decelerated" and "linear" eaters and demonstrated that decelerated eaters ate less food by the end of the meal and that the weight of each mouthful decreased but that the number of mouthfuls remained unchanged. These changes did not occur in linear eaters [5]. The results reported here differ in that the number of mouthfuls also decreased as the decelerated eaters approached the end of the meal. The frequency of chewing remained constant over the course of the meal in both groups, although the duration of the bursts of chewing actually increased by the end of the meal in the decelerated chewers. The distribution of chews within each burst of chewing was also similar between decelerated and linear eater with more chews in the second and fourth quartile of the chewing bursts compared to the first throughout the meal. This variation in the frequency chewing within bursts may be related to the different phases of the processing of food in the mouth; there are fewer chews when food is transported intraorally for subsequent chewing and during swallows [18,20].

In summary, decelerated eaters, as opposed to linear eaters, ate less food by the end of the meal, yet both groups showed a stable frequency of chewing throughout the meal, although the decelerated eaters chewed for a longer time during the last third of the meal when they ate the least amount of food (Fig. 5).

Thus, although the curve of cumulative food intake is different among decelerated and linear eaters, there appears to be no difference in chewing frequency. However, by using a piece of chewing gum, eliminating feedback from ingested food, we found that decelerated eaters chew at a higher frequency than linear eaters. The frequency of chewing the chewing gum that we observed was similar to that reported by others [29–35]. Both groups chewed at a lower frequency than when they were eating food, and the chewing frequency recorded with chewing gum correlated with the initial speed of eating recorded in the test with food. Hence, the lower initial speed of eating among linear than among decelerated eaters, which has been reported many times before [2–7,11], may be reflection of a reduced default frequency of chewing. This difference in chewing frequency was, however, masked over the course of the meal when the subjects were ingesting food.

We have hypothesized that linear eating is a behavioral risk factor for disordered eating that emerges from dieting and a high level of physical activity [7,15]. In support, the linearity of eating

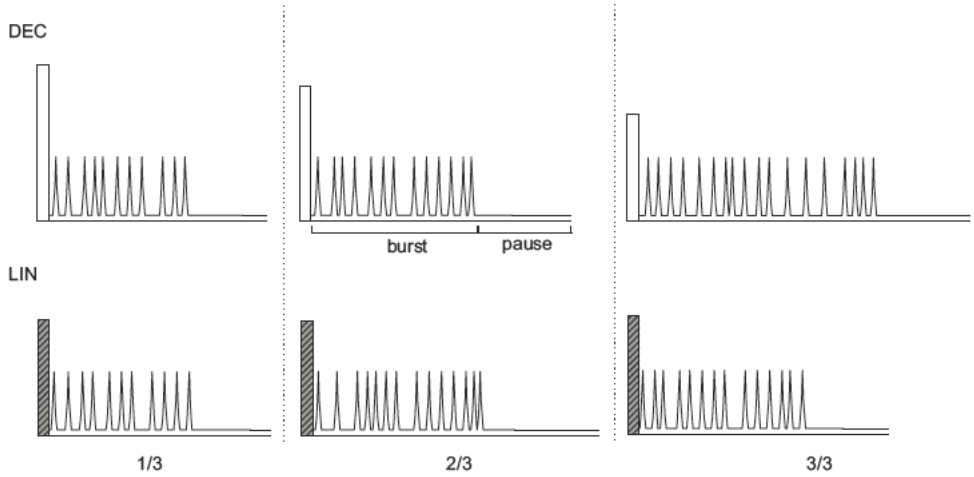

Fig. 5. Schematic representation of the pattern of mouthfuls (bar), a subsequent burst of chewing (spikes) and a pause during each third (1/3, 2/3 and 3/3) of a meal eaten by a woman selected for eating at a decelerating speed (decelerated eater, DEC) and in a woman selected for eating at a nearly constant speed (linear eater, LIN).

before a fast is inversely related to the amount of food eaten after the fast, and fasting increases the linearity of eating in women [7]. Conversely, most men are decelerated eaters, they eat more food and their eating becomes more decelerated after fasting [7]. Whilst this interesting sex difference in eating behavior may be related to the marked sex difference in eating disorders, it is not yet possible to relate to a sex differences in hormonal or metabolic parameters [7].

The neurobiology of the chewing rhythm has been well studied (reviewed in ref [21]); neural networks can drive the behavioral rhythm [19,36], which is normally modulated by sensory feedback [37–41,but see 42], an effect mediated via periodontal mechanoreceptors [43]. Although the consecutive rhythmic movements of the jaws during ingestion can be variable [38,44], as many as seven different patterns of chewing behavior have been suggested [45], the frequency of chewing is relatively constant [16,18,37,46].

Chewing affects mood and cognition by activating serotonin cell bodies in the dorsal raphe nucleus in the brainstem, which project to the orbito-frontal cortex (reviewed in Ref. [21]). Decreasing the firing of the dorsal raphe cells pharmacologically [47] increases anxiety [48]; conversely, activating these cells by chewing [49] decreases anxiety [50]. The same pharmacological treatment also activates the hypothalamic–pituitary–adrenal axis [51] an effect, which is counteracted by chewing [52]; dorsal raphe cells are hypoactive in a rat model of depression, an effect that may be mediated via an increase in corticotrophin-releasing-hormone [53,54].

Hence the neural engagement in chewing appears fairly well defined and the responses to experimental manipulations are consistent. The present study is the first to combine description of cumulative food intake and chewing and the results, therefore, can only be tentatively integrated with neural function. However, if that task is not attempted, unrealistic models may ensue [21,54]. The challenge will be to examine how these changes in neural function relate to the various patterns of chewing described in the present study, how feedback from food and gastrointestinal secretions modulates the chewing rhythm and if this knowledge can be translated into clinical practice.

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