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# Impact of spatial distribution on the sensory properties of multiphase 3D-printed food configurations

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ABSTRACT

The rise of 3D-printing technology is opening up new possibilities for arranging two or more sensorily distinct phases in a specific manner, and thus potentially creating new sensory experiences. Particularly interesting is the spatial configuration of multiple phases for adjusting flavor and texture perception without changing the overall composition, as such configuration would represent a step towards individualization. In the present study, different 3D configurations of two rheologically and texturally very distinct phases were investigated as to their effect on mechanical properties and sensory perception. Chocolate and cream cheese masses were arranged three-dimensionally (cube-in-cube; layered) by additive manufacturing and characterized by measuring penetration resistance as well as by hedonic, descriptive, and temporal dominance of sensation (TDS) methodologies. By comparing samples with identical phase ratios, three characteristic texture profiles could be generated. How much the samples were liked depended significantly on perceived mouthfeel/texture and product hardness. The mouthfeel was in turn determined by the 3D configuration of the phases. TDS characterization showed either two or three dominance areas of one of the phases, depending on whether chocolate or cream cheese was perceived initially. While the dominance time of chocolate increased with increasing chocolate fraction in samples with chocolate as the external phase, the dominance time of cream cheese in samples with cream cheese as the external phase hardly changed with increasing phase fraction. This was mainly attributed to the very different rheological phase properties of cream cheese and chocolate. Based on the TDS evolution at the later stages of consumption that is rather independent of the initial configuration, the renewal of the relevant interface in the oral cavity was mainly determined by the mixing kinetics of both phases, and secondarily by what phase was perceived to be dominant before a phase dominance change took place. This study shows that in defining the 3D configuration of phases with differing rheological properties, there is considerable potential for adjusting the sensory properties. This is a step towards broader coverage of consumer needs through 3D product design without the need for formulation adjustments.

## 1. Introduction

Three-dimensional printing (3D-printing), also called additive manufacturing, has taken a foothold in multiple fields, including the space, medical, military, and manufacturing sectors (Yuan et al., 2019; Flowers et al., 2017; Bose et al., 2013; Yang et al., 2017; Godoi et al., 2016; Dankar et al., 2018). More recently,

3D-printing of food has undergone rapid development, as reflected by the surge of publications on this subject in recent years (Zhang, Pandya, McClements, Lu, & Kinchla, 2021). Many of the principles applied when printing food are derived from those used for printing organs or biomedical tissues (Godoi, Prakash, & Bhandari, 2016). According to Ma and Zhang (Ma & Zhang, 2022), modifying geometric designs and varying the spatial arrangement of ingredients are common ways of altering sensory properties through the use of additive manufacturing. As a consequence, 3D-printing is considered a promising tool for personalizing food and pleasing a variety of customers (Godoi et al., 2019; Ma and Zhang, 2022).

A plethora of studies have investigated how modifying structure on a macroscopic scale can affect instrumental texture (Derossi et al., 2019; Liu et al., 2018; Liu et al., 2020; van Bommel et al., 2019; Vancauwenberghe et al., 2017). However, only a limited number of

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publications have focused on sensory properties and perceived texture using food 3D-printing. Zhu et al. (Zhu, Ribberink, De Wit, Schutyser, & Stieger, 2020) deposited a chocolate layer of varying levels of thickness onto rice waffles by 3D-inkjet printing and showed a link between the modification of bite-to-bite experience, the perception of sweetness, and overall liking. In another study, Zhu et al. (Zhu et al., 2021) introduced 3D-printing to print protein bars with different chocolate fillings, thereby demonstrating that infill pattern significantly influenced both instrumental and sensory texture.

Assessing composite food, for example, of granola chunks with butter, or of milk with corn flakes, reflects the true experience of eating more naturally than assessing single foods, since perceptions can unfold over time during consumption (van Eck et al., 2019). To describe the temporal complexity of composite food consumption, temporal dominance of sensation (TDS) has been shown to be a descriptive multi-attribute methodology able to deal with the interactions between multiple attributes (Pineau et al., 2009). Few studies have attempted to investigate the sensory perception of composite foods (van Eck et al., 2019), and to our knowledge, only one study has combined it with additive manufacturing. Khemacheevakul, Wolodko, Nguyen, & Wismer (2021) used TDS to evaluate the temporal sensory profile of 3D-printed chocolate prototypes made up of layers of variable sweetness. The layering order influenced temporal sensory and sweetness perception, without altering overall liking scores.

The aim of the present study was to determine the effect of the macroscopic, hierarchical structuring of cream cheese and chocolate on the temporal perception of the attributes linked to both distinct phases. Further, the prototypes, 3D-printed by dual nozzle deposition were characterized by instrumental, Check-All-That-Apply, and liking scores to link descriptive, hedonic, and instrumental data. It was hypothesized that structuring had an influence on not only the appearance but also the attributes appearing during oral processing of food (such as mouthfeel or taste), and thus created different categories of foods.

## 2. Material and methods

### 2.1. Sample preparation

Chocolate (Cremant 55%, Chocolat Frey, Switzerland) and cream cheese (Philadelphia cream cheese, Kraft AG, Switzerland) were both bought at Migros (Bern, Switzerland). Up to seven 3D configurations based on two phases (chocolate and cream cheese; cube-in-cube, at five different phase fractions (0, 25, 50, 75 and 100%v/v) and a layered configuration) were prepared. Typical examples for cube-in-cube and layered configurations are illustrated in Fig. 1b and c. Cube-in-cube samples were arranged with an inner cube of one phase surrounded by a shell of the other phase. They were labeled following the syntax $\textit{Outer Phase}_{Frac}$, where *Outer Phase* was either *Choco* or *Cream*, representing either chocolate or cream cheese, and *frac* referred to the volumetric fraction of the outer phase (Example: $Choco_{75}$ denoted a sample with chocolate as the outer phase with 75%v/v of chocolate compared to the total volume and the inner cube of cream cheese amounts to the remaining 25%v/v). In the case of a layered configuration, only ($L_{50}$) was manufactured, where *L* denoted *layered* and the 50 represented the equal volumetric distribution of both chocolate and cream cheese.

Solid chocolate was added to a piping bag and placed into a water bath at 45 °C until completely melted. The bag was then transferred to a 32 °C water bath, where the mass was occasionally stirred by hand in the bag. In order to temper the chocolate, 2.67 g of chocolate shavings (Cremant 55%, Chocolat Frey, Switzerland) were added to 97.33 g of the melted chocolate and stirred by hand for three minutes. The tempered chocolate was transferred into a pre-heated (32°C) stainless steel cartridge, while the cartridge was vibrated on a vortex (Mini Vortex Stirrer, LBX Instruments, Switzerland) to avoid gas inclusions. Like the chocolate, the cream cheese was also placed in a piping bag, vacuum sealed (40 mbar) to remove air inclusions, and transferred to the cartridge at room temperature.

### 2.2. 3D-Printing

The cubical samples with a size of $20x20x20mm^3$ were printed either as cube-in-cube configurations with different volumetric fractions or in a layered configuration (Fig. 1b and c). Both masses were printed with stainless-steel syringes, equipped with a 15 mm long nozzle with an inner diameter of 1.8 mm (Sigrist & Partner AG, Matzingen, Switzerland), except for the samples with 25%v/v fractions, which were extruded with a 0.65 mm diameter nozzle (Sigrist & Partner AG, Matzingen, Switzerland). The temperature of both chocolate (32.5 ± 1°C) and cream cheese (25 ± 1 °C) was regulated with an aluminum heating jacket equipped with two Peltier elements (102–1674-ND, Digikey, United States). 3D-printing was conducted with a custom-built three-

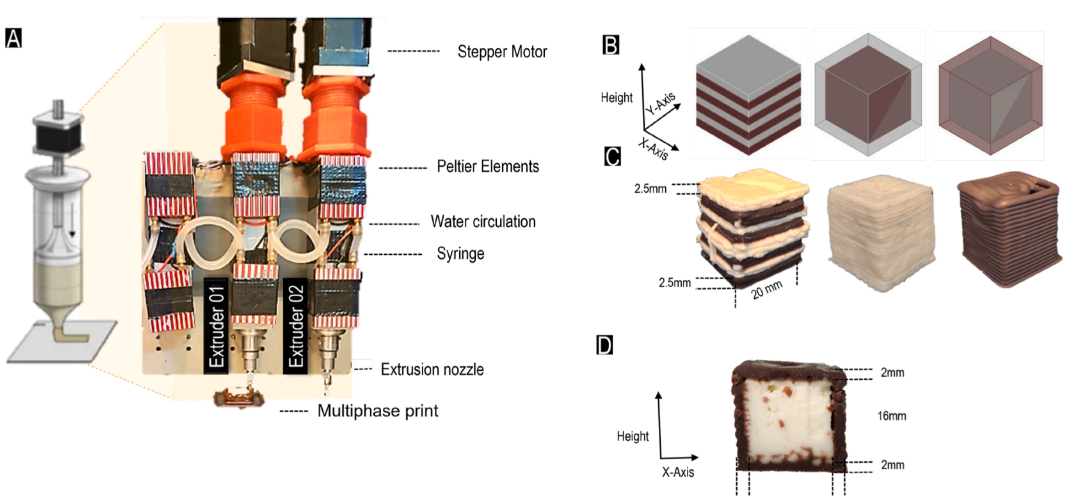


**Fig. 1.** (A) Closeup of the printhead with two extruders installed, and of the thermoelectric and mechanical units. The 3D-printer operated by mechanically-induced displacement, as illustrated in the diagram on the left. (B) All composites were additively built up according to the three different CAD cubical shapes, with the dimensions for the cube-in-cube configuration varying from 12.53 (25 %v/v inner phase) to 183 mm3 (75 %v/v inner phase). The layer heights and dimensions were exemplary shown for the layered samples. (C) Appearance of the final composites, 3D-printed according to the CAD shown in (B). (D) Cross section of the $Choco_{50}$ sample to illustrate the infill pattern of the various composites.

axis cartesian printer (designed by the Institute for Print Technology, Bern University of Applied Sciences), equipped with two independent extruders (see Fig. 1a and Kistler, Pridal, Bourcet, and Denkel (2021). The printer was placed in a cooling chamber (KK-1000 CHLT, Kambic, Slovenia), adjusted to 5 °C. The Repetier-Host software was used to control the printing process, and Slic3r to generate the G-Codes. Prior to further instrumental or sensory tests, all samples were stored at –22 °C.

### 2.3. Texture analysis

Penetration tests were performed using a TA.HD Plus Texture Analyser (Stable Micro Systems, UK), which was equipped with an extended craft knife with a blade thickness of 0.6 mm. Prior to texture analysis, all samples were thawed and tempered to 20 ± 1 °C for 2 h. Mimicking early oral processing conditions, all composites were placed on the texture analyzer similarly to the positioning of the composites in the mouth. In the case of the layered sample, the chocolate layer was placed on the bottom while the cream cheese layer was positioned on top. While the blade penetrated the sample at a test speed of 1 mm/s, data was recorded in the Exponent Stable Micro Systems software (version 6.1.14.0). A total of two batches, containing 16 replicates, were analyzed.

### 2.4. Sensory evaluation

An overview of all performed experiments including the set of samples investigated, the number of panelists and the data analysis is detailed in Table1. Every participant signed a consent form before starting the sensory evaluations.

#### 2.4.1. Consumer tests

One-hundred-and-twenty sensory participants from Bern University of Applied Science, School of Agricultural, Forest and Food Sciences, were recruited via email to conduct consumer testing. The tests were carried out in a sensory laboratory in accordance with ISO 8589 (1988), with a balanced and randomized test design. Participants were monadically provided with the samples $Choco_{50}$, $Cream_{50}$, and $L_{50}$ on disposable plastic plates encoded with a three-digit-code. They were instructed to place the whole product in their mouth. For the layered sample, the participants were instructed to place the sample with the chocolate side on the tongue while the cream cheese was on top. Biting was not allowed, but tongue movement was permitted. After consumption, they completed the questionnaire, which was divided into a hedonic rating part, and a Check-All-That-Apply (CATA) part. In the first four questions, the panelists were asked to rate the overall liking, mouthfeel, appearance and taste, using a linear nine-point scale, ranging from one ("dislike extremely") to nine ("like extremely"), with a score of five anchored as neutral ("neither like nor dislike"). No explicit definition of the above-listed four descriptors was given. In addition, the participants answered a CATA questionnaire, where they had to choose among a list of 12 pre-defined attributes those that best described a product's characteristics (see Tables 1 and 2 in appendix). In between the different samples, the participants were requested to rinse their mouth with water and eat an unsalted cracker.

The hedonic data were evaluated in Graphpad Prism (Version 9.2.0), using a multicomprative non-parametric Friedman test. Significances between the samples were tested with a post-hoc Wilcoxon test. CATA data were visualized graphically with a Principle Component Analysis (PCA) of a contingency table. The selection of principal components was justified based on a Kaiser and Scree plot. A contingency table was created counting the frequency of each pre-selected term from each of the 120 participants. A Cochran's-Q test was performed to identify significant differences among the samples for each of the CATA terms. Correlation lookup between the CATA terms and the hedonic ratings was investigated with a Spearman correlation matrix.

#### 2.4.2. Temporal dominance of sensation

Eight to ten trained panelists (all women, with ages from 24 to 59) participated in the study. The participants were submitted to preliminary studies, degusting a piece of chocolate and a tea spoon of cream cheese to familiarize themselves with the sweet/bitter attributes of chocolate and the salty/sour ones of cream cheese. They were instructed to rate the most dominant attribute, that is, the most striking perception at various time points of consumption. After acquainting themselves with the dominant attributes of chocolate/cream cheese, the panelists were trained in a two hour session on the temporal dominance of sensation (TDS) methodology. Once they had completed the training, the panelists tested each of the samples four times during four subsequent sessions. All samples were produced a week prior to the analysis and stored at –22 ± 1 °C, before later being thawed and tempered at 20 ± 1 °C before testing. Samples were presented in monadic order on disposable plastic plates that were each encoded with a three-digit-code. The panelists were asked to put the sample in their mouth - with the chocolate layer directed to the mouth in the layered composites - and start the evaluation without biting, noting the most dominant attribute over the course of the sensory tasting. Each time they perceived a change in dominance, they updated their notation of the attribute until the sample was fully used up. All data were recorded using FIZZ software

**Table 1**
Overview of the performed experiments (analytical and sensory tests) specifying the set of samples used, the number of panelists (only for sensory analysis), the data analysis (only for sensory analysis) and relevant remarks.

| Test | Samples | Number of Panelists | Analysis | Remarks |
|---|---|---|---|---|
| *Analytical Test* | | | | |
| Texture Analysis | $Choco_{75}$, $Choco_{50}$, $Choco_{25}$<br>L50<br>$Cream_{75}$, $Cream_{50}$, $Cream_{25}$ | – | – | – 16 Replicates |
| *Sensory Test* | | | | |
| Hedonic Test | $Choco_{50}$<br>L50<br>$Cream_{50}$ | 120 | Friedman Test, Post-Hoc Wilcoxon Test | - All tests were conducted based on ISO 8589 (1988) - No replicates |
| Check-All-That-Apply (CATA) | $Choco_{50}$<br>L50<br>$Cream_{50}$ | 120 | Contingency Table, Cochran's Q Test,<br>Correspondence Analysis | - ISO 8589 (1988)<br>No replicates |
| Temporal Dominance of Sensations (TDS) | $Choco_{75}$, $Choco_{50}$, $Choco_{25}$<br>L50<br>$Cream_{75}$, $Cream_{50}$, $Cream_{25}$ | 8–10 | Generalized Additive Model with Penalized Regression | - ISO 8589 (1988)<br>Four Replicates |

Version 2.40G (Biosystemes, Couternon, France), where the start and end of each panelist's sensory tasting was standardized on a time scale from 0 to 100.

As sour and salty unambiguously described the cream cheese phase, and sweet and bitter clearly outlined chocolate taste, the TDS curves were aggregated to chocolate and cream cheese to obtain averaged curves for each product. Since the two phases were clearly identified by the two taste attributes described above, no inquiries were made about textural characteristics in the TDS evaluation. The consumption time was standardized between 0 ("first perception") and 1 ("No more perception") (Lenfant, Loret, Pineau, Hartmann, & Martin, 2009). Data of the attributes bitter, sweet, sour, and salty were aggregated and grouped in bitter/sweet and sour/salty, to represent chocolate and cream cheese, respectively. The generalized linear additive model (LinearGAM) of the pyGam package in Python was used to smooth the graph of dominance over time (Wood, 2017). Smooth terms in LinearGAM were generated based on fifteen splines and 1000 iterations, using penalized regression splines to automatically find the best two-dimensional grid (LinearGAM.gridsearch(x,y)). Two lines were added to the TDS figures to differentiate between random and significant data. The first line drawn in the TDS figures, known as the "chance level", is the dominance rate that an attribute can obtain by chance, where $P_0$ is equal to $1/p$, with $p$ being the number of attributes (Pineau et al., 2009). The second line corresponds to the "significance level", that is, the minimum value required to consider a proportion as significant. It was calculated using the confidence interval of a binomial proportion, based on normal approximation (Pineau et al., 2009):

$$P_s = P_0 + 1.645\sqrt{\frac{P_0(1-P_0)}{n}}$$

where $P_s$ is the lowest significant proportion value ($\alpha = 0.05$) at any point in time for a TDS curve, and $n$ the number of subjects × replication.

Various additional informations, such as the onset of sensation or the crossover trend, were constructed by linear regression using the Jupyter Notebook package sklearn.

## 3. Results and discussion

### 3.1. Mechanical properties

Texture analytical tests were performed on all samples and the force-distance profiles shown in Fig. 2 were thus obtained. Samples with cream cheese as the outer phase (*Cream*$_{25}$, *Cream*$_{50}$, and *Cream*$_{75}$) exhibited two peaks, the first being the highest (Fig. 2b). While the test specimen was able to penetrate through the cream cheese shell with low penetration resistance, high penetration forces were required to split the solid inner chocolate cube. With the exception of *Cream*$_{25}$, the penetration resistance maximum decreased as the inner phase fraction decreased, while at the same time the peak maximum was reached at higher penetration depth. It was visually confirmed that due to their low penetration resistances, both the top and bottom cream cheese layers were largely penetrated or compressed/elongated, before the inner chocolate cube was no longer able to resist the penetration forces. A second peak, which occurred in all the samples, showed significantly lower forces due to additional fragmentation of the remaining chocolate cube left over from the previous non-vertical fracturing.

Samples with fresh cheese as the inner phase (Fig. 2a) consistently exhibited considerably lower penetration resistances. Peaks appearing at the beginning and towards the end of the curve signal the penetration of the uppermost and lowermost outside chocolate layers, respectively, whereas the intermediate parts of the curves reflect the penetration of thin chocolate structures of the shell in combination with the penetration resistance of the cream cheese inside. The thinner the walls of the outer cube, the lower the overall level of penetration resistance became and the lower the peaks at the beginning and end. In the case of *Choco*$_{50}$, the breakage of the upper chocolate layer occurred only after partial compression of the inner cream cheese filling, so that the actual breakage peak was delayed and occurred at increased penetration depth (as visually confirmed during the experiment).

The layered sample *L*$_{50}$, on the other hand, showed a total of four peaks, which corresponded to the number of chocolate layers in the sample. The first peak was observed at a penetration depth of about 8 mm, illustrating that over 70% of the cream cheese was squeezed out of the sample before any penetration or breakage of the chocolate layers occurred.

### 3.2. Sensory characterization

#### 3.2.1. Consumer tests

Results of the hedonic ratings are shown in Fig. 3. The comparison of the intensity of hedonic attributes revealed strong differences between the samples *Cream*$_{50}$, *Choco*$_{50}$, and *L*$_{50}$. Appearance was rated highest for layered samples (mean = 6.81) and they were thus significantly more appealing compared to *Choco*$_{50}$ (mean = 6.12) and *Cream*$_{50}$ (mean = 5.46). Taste, however, which was not terminologically further defined for the participants, was not significantly different between the samples. For the attributes mouthfeel and overall liking, *Choco*$_{50}$, and *L*$_{50}$ were rated significantly higher than *Cream*$_{50}$. No preference test was carried out for this study; however, a non-parametric ranking showed that for overall liking, 37 participants scored *Cream*$_{50}$ highest, 65 participants *Choco*$_{50}$, and 51 participants *L*$_{50}$, findings which are consistent with the data in Fig. 3b.

The non-parametric Spearman rank correlation matrix in Fig. 4 highlighted a mutual and significant similar trend between overall liking and mouthfeel (Spearman r = 0.71, p < 0.01). In addition to mouthfeel, taste (r = 0.91, p < 0.01) showed a strongly positive correlation with

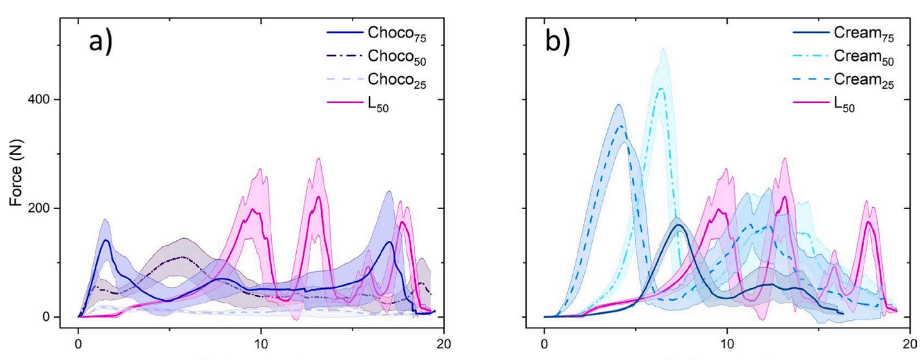


**Fig. 2.** Penetration force-distance tests of the seven sample configurations, divided into Choco and L configurations on the left (a), and Cream and L configurations on the right (b). The layered sample is shown in both graphs (identical data) as it had both cream cheese and chocolate as outer phase and could not be allocated to only (a) or (b). The colored area surrounding each curve represents its standard deviation.

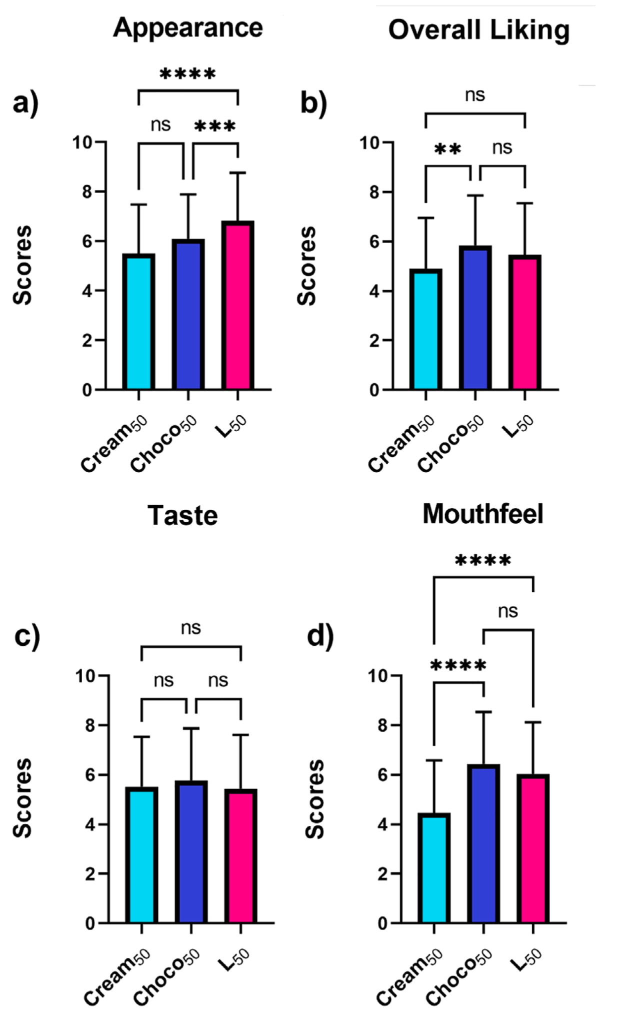


**Fig. 3.** Hedonic rating of three samples with different 3D configurations but equi-volumetric fractions of chocolate and cream cheese, $Cream_{50}$ (cyan), $Choco_{50}$ (blue), and $L_{50}$ (pink). The hedonic rating comprised appearance (a), overall liking (b), taste (c), and mouthfeel (d). Significances were tested with a post-hoc Wilcoxon test. Non-significant differences are abbreviated "ns", and the number of asterisks (*) indicates the different significance levels (* <0.05, ** <0.01,*** <0.001,**** <0.0001). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

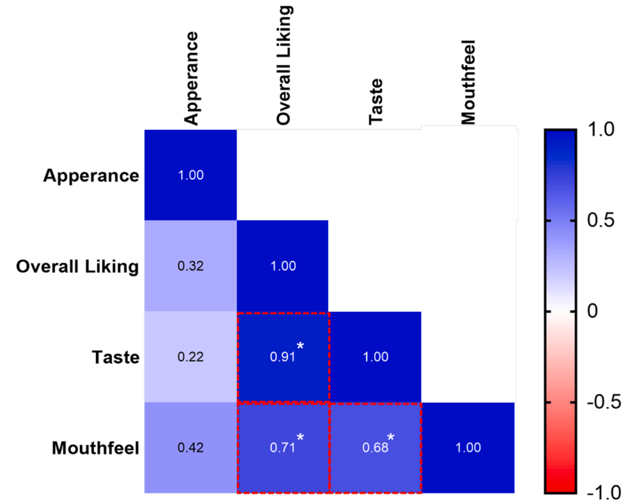


**Fig. 4.** Spearman correlation matrix between the hedonic attributes (i) appearance, (ii) overall liking, (iii) taste, and (iv) mouthfeel. The colorbar represents the direction and strength of correlation, and the asterisks indicates significant correlations. The red dashed frames denote significant correlations between hedonic attributes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

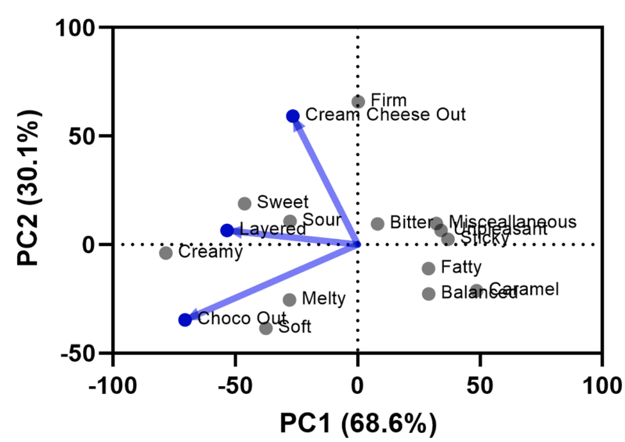


**Fig. 5.** Principal component analysis (PCA) plot. The blue vectors represent the loadings of $Choco_{50}$, $Cream_{50}$ and $L_{50}$, and the grey dots the PC score. The proportion of variance explained by the eigenvector in the x- and y-axes is written beside PCA1 and PCA2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

overall liking. In contrast, contrary to expectation, overall liking showed a low correlation ($r = 0.32$, $p > 0.05$) with appearance. In general, appearance did not seem to affect sensory perceptions, even though the samples were optically very different (Fig. 1b) and no efforts were made to avoid optical differences during the sensory tests. As consumers combine foodstuffs with distinct properties and compositions every day during a meal or within a bite (e.g., bread is usually combined with a spread), it is assumed that the unfamiliarity of the combinations of cream cheese and chocolate resulted in the domination of the in-mouth processing attributes (taste and mouthfeel) over visual appearance.

Contrary to a study by Zhu et al. (2021), where macroscopic adjustments of printing patterns of a two-phase chocolate protein bar configuration modified perceived texture without affecting liking, it is assumed that unaccustomed food pairings in our study influenced in-mouth properties (somatosensory and taste) to such an extent as to dominate overall liking significantly.

The strong influence of mouthfeel properties is also mirrored in the CATA questionnaire, where the participants rated the characteristics of the samples out of a list of 12 pre-defined attributes, with multiple answers allowed (see Tables 1 and 2 in appendix). The evaluation of the CATA data by means of a biplot (Fig. 5) uncovered the strong influence of mouthfeel on the perception of the samples, with hardness alone contributing 52.2% (data not shown) to PC 2. As a result, hardness of $Cream_{50}$ ($n = 102$ panelists), $L_{50}$ ($n = 43$ panelists) and $Choco_{50}$ ($n = 18$ panelists) was rated with different frequencies. Likewise, creaminess (32.6%) was the most prominent contributor of PC 1, rated more frequently in $Choco_{50}$ ($n = 103$ panelists) and $L_{50}$ ($n = 88$ panelists) compared to $Cream_{50}$ ($n = 59$ panelists). Even though the protocol did not include biting, the samples were slowly pressed and moved between the tongue and palate, where similar breakage and collapse probably occurred. The comparison between the instrumental mechanical properties and the hardness ratings in CATA revealed a strong positive association between maximum peak force in penetration tests and sensorially perceived hardness. As such, the good agreement reflected the ease of the untrained panel in distinguishing between the different macroscopic configurations. Such observations were made in a study (Zhu et al., 2021), where hardness was the only attribute of 3D-printed chocolate-protein bars, out of a list of liking, hardness, and chewiness, that correlated significantly to the texture profile analysis.

Contrary to the modalities (sour, sweet, and bitter), the textural attributes melting ($p < 1.26e{-}11$) and stickiness ($p < 0.0006$) deviated significantly between the 3D configurations. For both attributes, $Cream_{50}$ was perceived as more sticky and less melting than the two other configurations. The same trend in unpleasantness as in the hedonic ratings was observed, from $Choco_{50}$ ($n = 11$ panelists) as the least unpleasant, to $Cream_{50}$ ($n = 35$ panelists) as the most unpleasant sample. Both, CATA questionnaire and hedonic ratings indicate that strong deviations in textural attributes, created by different 3D configurations, alter overall liking.

### 3.2.2. Temporal dominance of sensation

Temporal dominance of sensation (TDS) for seven different sample configurations are depicted in Fig. 6. Irrespective of its volumetric fraction, the outer phase dominated at the early stages of perception for $Choco_X$ samples. The $Choco_{25}$ constituted an exception, as low mechanical stress during oral processing was already sufficient to break the thin shell and release cream cheese, as mirrored in the low penetration resistance in Fig. 2a. The atypical temporal sensation of this configuration, where instantaneous mixing between both phases occurred, is also reflected in Fig. 7a, where the dominance scores between 0 and 10% of consumption time were interpolated linearly to calculate the slope for perception onset.

Concerning the onsets of the cream-phase tastant attributes in $Cream_X$ and of the chocolate tastant attributes in $Choco_X$ samples, the slopes for increasing dominance scores appeared to be quasi-independent of the ratio of both phases, leveling out between 7 and 9 for the cream cheese attributes, and 6 and 7 for the chocolate attributes. The observation of lower onset slopes in $Choco_X$ configurations was probably related to the substantial thermal energy required to melt the fat crystal network and transport tastants from the chocolate matrix to the mucous layer membrane (Mantihal, Prakash, Godoi, & Bhandari, 2017). The 3D configuration of the samples not only influenced the slope of perception onset, but also the maximum dominance score and the duration of the first dominance regime. Accordingly, the importance of the outer shell fraction was manifested by an increase from $Choco_{50}$ to $Choco_{75}$, both of the absolute dominance of the first dominance regime (0.82–1.00) and of its duration (0.38–0.58).

Recently, Wu and Zhao (2020) modeled sweetness and saltiness with a porous-medium human tongue model and found a strong correlation between sensory data and effective diffusivity, if convection was reduced. In our experimental setup, fluid movement was limited due to non-biting, non-complex chewing conditions and the differences in diffusivities in water- and oil-continuums were assumed to have strongly contributed to the delay of occurrence of the first maximum dominance of the chocolate attributes, which took two to three times longer to appear than the dominance of the cream cheese attributes.

Exiting the first contact regime, sample configurations with a chocolate outer phase ($Choco_{50}$, $Choco_{75}$; sample $Choco_{25}$ immediately collapsed due to thin shell structures) exhibited a boundary regime with inverted dominance regimes compared to the initial and final regimes. The magnitude of crossover from one phase to another varied between

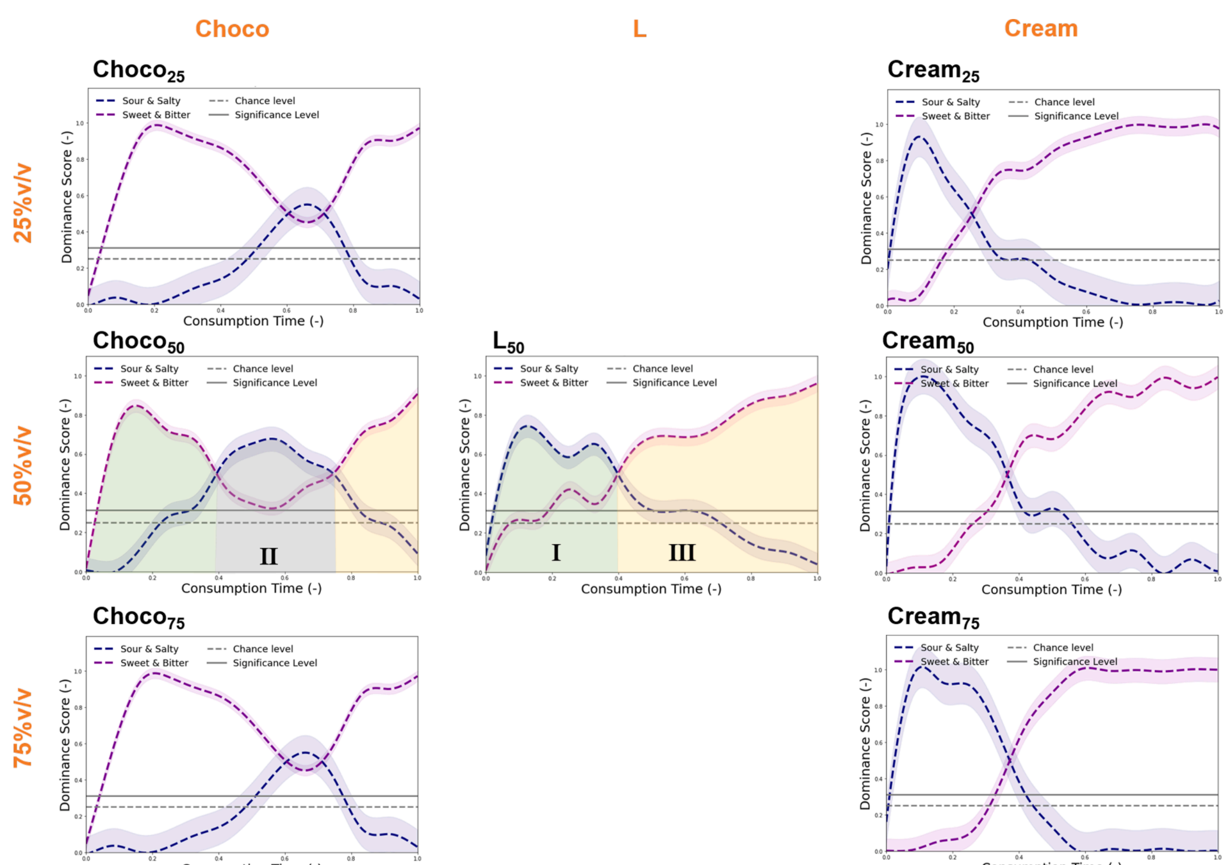


**Fig. 6.** Temporal dominance of sensation of seven sample configurations, varying from left to right in the composition of the outer phase and from top to bottom in the volumetric ratio of chocolate (from 25%v/v on top to 75%v/v in the bottom). The two dashed lines and the colored areas surrounding them represent the aggregated cream cheese attributes "sour/salty" (dashed blue line), the chocolate attributes "sweet/bitter" (dashed purple), and their respective 90% confidence intervals. Chance and significance levels are shown with the grey full and dashed lines, respectively. The different consumption regimes are shown for two exemplary plots $Choco_{50}$ and $L_{50}$ with three different regimes. Regime I represents a first contact regime, regime II a boundary regime, and regime III a mixed regime. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

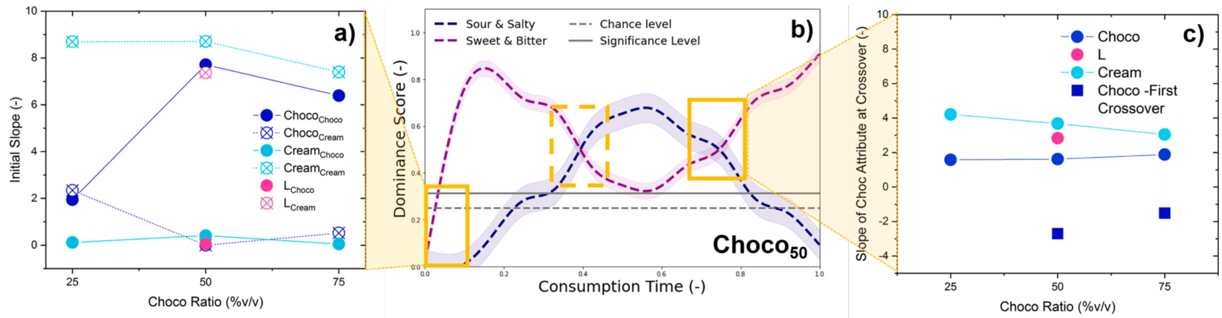


**Fig. 7.** Convolution of TDS data for different times during consumption, with an exemplary curve for $Choco_{50}$ to visualize the different regions of interest. On the left (a), the characteristic slope of the onset of sensation for each sample configuration of the TDS curves is extracted, by a linear fit within 0 to 10% of consumption time. $Choco_{Choco}$: chocolate shell, slope of chocolate curve; $Choco_{Cream}$: chocolate shell, slope of cream cheese curve; $L_{Choco}$ or $_{Cream}$: layered sample, slope of chocolate curve or cream cheese curve; $Cream_{Choco}$: cream cheese shell, slope of chocolate curve; $Cream_{Cream}$: cream cheese shell, slope of cream cheese curve; A comparable interpolation for the final crossover between dominance regimes is represented on the right (c)). Two crossovers occur for the samples $Choco_{50}$ at the start and end of the boundary regime. For these two specimens, initial crossover slopes are added as blue squares. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1.97 and 4.02 (see Fig. 7c), but were nearly independent of phase ratio or material of the outer layer. Also considering that the crossover slopes were significantly smaller than those in the first contact regime, we assume that the regime change was preceded by interfacial renewal and was governed by convective mixing. Samples with fresh cheese on the outside showed a more rapid phase change. The causes of this difference are unclear. Possibly, chocolate can create a longer lasting thin film that cannot be removed from the interface, at least not completely, when cream cheese approaches it, and thus maybe creating a diffusion resistance that slows down the perceptual change. However, the small number of data points does not allow a reliable conclusion to be drawn. Besides their similar initial behavior, chocolate attributes dominated for all samples at the end of consumption, which suggests the possible in-mouth formation of a lubricating oil layer (Boehm, Yakubov, Delwiche, Stokes, & Baier, 2019) and/or a delayed melting/mixing of chocolate.

Convolution of the combined chocolate attributes to sweetness and bitterness revealed a similar temporal dominance trend that deviated strongly towards the end of consumption, where there is a prevailing dominance of bitterness. Such observations are surprising, since Palazzo and Bolini (2014) and Oberrauter, Januszewska, Schlich, and Majchrzak (2018) found comparable temporal profiles of bitterness and sweetness. Due to the presence of (−)-epicatechin, and (+)-catechin and their high antioxidative capacity, a high cocoa content is also associated with astringency (Kennedy & Heymann, 2009). Hence, we believe that during this study the onset of bitterness at the later stages observed in the TDS curves was somewhat linked to the strong onset of astringency. Considering the differences in mouthfeel rating (see Fig. 2), and the similarity in temporal evolution of the equally weighed samples $L_{50}$ and $Cream_{50}$ in the final regime, we assume that hedonic mouthfeel perception is shaped in the early regime of food oral processing.

## 4. Conclusions

In the present study, we were able to show that 3D configuration of two phases can change both the taste and texture sensory properties. Two typical dominance profiles were found for the combination of cream cheese and chocolate, exhibiting either one or two dominance changes, depending on the 3D configuration. In principle, it was thus possible to demonstrate that temporally differentiated sensory profiles can be generated by altering the 3D configuration of two sensorially different and non-mixed phases in otherwise identically composed samples.

All dominance profiles showed chocolate dominance towards the end of the normalized consumption times, preceded in all cases by cream cheese dominance, regardless of which phase was the outer phase. Dominance profiles with two phase changes occurred only when chocolate was the outer phase and did not immediately mechanically disintegrate in the mouth, that is, when the chocolate fraction was high. Comparing samples of the same overall composition, we observed a clear temporal dominance of the chocolate phase, which we attribute to the fact that cream cheese, being a water-continuous, non-solid system, is more quickly diluted by saliva and swallowed than chocolate. This assumption suggests that, in further studies, a focus should be placed on investigating in greater depth the impact of both the quantity and the kinetics of salivation, in conjunction with the rheological properties of the phases involved. This study also revealed that the liking of the samples depended mainly on their texture. This is understandable, since the texture differences between chocolate and cream cheese are considerable, and so the mouthfeel was unfamiliar to the subjects. We assume that, when masses which are less distinct texturally, are combined, the importance of texture decreases while that of the sensory profiles increases.

When looking at the sequence of the dominance scores of both phases during the transition from one phase to another, we found slopes of a similar order of magnitude, regardless of the phase from which the dominance change originated. On the other hand, the initial dominance evolution, that is, the initial occupancy of the interface, occurred two-to-three times faster and was determined by the external phase. We conclude that the renewal of the interface in the oral cavity when the phase dominance changes is rather independent of which phase loses or gains dominance. It seems to follow the same pattern in both cases, and thus to be determined by mixing rather than by diffusion. However, as samples with chocolate on the outside exhibited a slower phase change, we also suspect a first contact effect that should be investigated further. However, the reservation must be made that the sum total of all the dominance data was interpreted as the degree of individual perception, which is admissible from our point of view since the individuum always had to decide in favor of the dominance of either one phase or the other.

This study clearly shows the potential of the 3D design of products. It also opens up possibilities for individualizing food products without changing their composition. However, it remains to be seen what significance temporally resolved sensory profiles and differences in 3D configurations have with regard to sample preference, and whether different consumer needs can thus be more broadly met. If this is the case, the overall acceptance of a product could be increased by simply offering different 3D designs, without changing its composition.

*CRediT authorship contribution statement*

**Johannes Burkard:** Conceptualization, Investigation, Methodology, Software, Validation, Visualization. **Akshay Nain Shah:** Data curation, Formal analysis, Investigation. **Eugenia Harms:** Investigation, Methodology. **Christoph Denkel:** Conceptualization, Methodology, Validation, Funding acquisition, Supervision.

## Declaration of Competing Interest

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

## Data availability

The data that has been used is confidential.

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## Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodqual.2023.104850.

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