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Effect of oral burn on dynamic taste, flavor and mouthfeel perception of tomato soups, curried rice and beef patties

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ABSTRACT

This study aimed to determine the effect of oral burn on temporal taste, flavor and mouthfeel perception of tomato soups, curried rice and beef patties. These foods were prepared without (control) and with capsaicin (low/high capsaicin concentration) or ground dried chilies (low/high chili concentration). Temporal-Check-All-That-Apply (TCATA; n=73; duplicate) was used to quantify dynamic sensory perception. The maximum citation proportion (Cit_{max}) and/or area under the curve (AUC) of numerous taste, flavor and mouthfeel attributes were significantly reduced demonstrating suppression of these perceptions across three foods and two trigeminal stimuli. The time to reach maximum citation proportion (T_{max}) of sweetness, saltiness and creaminess of curried rice and beef flavor and fattiness of beef patties were significantly affected by oral burn but only to a small extent suggesting that the temporal build up of taste, flavor and mouthfeel was influenced only to a limited extent. In contrast, the time period after which the citation proportion decreased to half of the maximum citation proportion ($T_{½max}$) decreased significantly and considerably with burn for sweetness, sourness, tomato flavor and creaminess of tomato soups; for sweetness, rice flavor, coconut flavor and hardness of curried rice; and for beef flavor, hardness and fattiness of beef patties demonstrating that oral burn shortened the lingering of taste, flavor and mouthfeel perceptions. We conclude that in tomato soups, curried rice and beef patties oral burn suppresses taste, flavor and mouthfeel perceptions, reduces the lingering of taste, flavor and mouthfeel perceptions while the temporal build up of these perceptions is influenced only to a limited extent.

1. Introduction

Chili peppers are one of the most commonly encountered chemesthetic culinary spices. Its oral burn is increasingly being recognized to relate to flavor complexity, overall flavor impression, consumer acceptability and satisfaction (Green, 1996; Spencer et al., 2018; Spencer & Dalton, 2020; Spencer & Guinard, 2018). The burn produced by chili or capsaicin has been previously described as “burning”, “warm”, “numbing”, “tingling”, “stinging”, and to a much lesser extent, “piercing”, “biting”, and “itching” (de Araujo et al., 2005; McCabe & Rolls, 2007; Rolls & Baylis, 1994; Spencer & Dalton, 2020; Thomas-Danguin et al., 2016). Different static and dynamic sensory methods have been used to characterize oral burn of various trigeminal stimuli (Bartoshuk et al., 2004; Boudreau et al., 2009; Byrnes & Hayes, 2013, 2015; Hayes et al., 2013; Ludy & Mattes, 2011, 2012; Lyu et al., 2021; Nolden & Hayes, 2017; Prescott et al., 1993; Schutz & Cardello, 2001; Stevenson & Yeomans, 1993).

Several temporal sensory techniques have been employed to track dynamic changes in oral burn over time (Lawless & Heymann, 2013; Ward, 2016). Early Time-Intensity (TI) studies generally compared the evolution of burn intensity over time between solutions of different trigeminal stimuli or various chili peppers (Carden et al., 1999; Cliff & Heymann, 1993; Green, 1989; Hutchinson et al., 1990; Lawless, 1984; Lawless & Stevens, 1988; Nasrawi & Pangborn, 1990a). Later studies applied the TI methodology to explore cross-modal interactions between gustatory, olfactory and trigeminal perceptions. Oral burn reduced sweetness intensity of sucrose solutions, bitterness intensity of bitter tastants and strawberry flavor intensity of strawberry flavor solutions (Green & Hayes, 2003; Nasrawi & Pangborn, 1989; Prescott & Francis, 1997; Prescott & Stevenson, 1995). Capsaicin enhanced aroma perception of flavored solutions of 3-methylbutanal considerably although capsaicin had no impact on in-nose aroma release concentration (Yang et al., 2021). Recently, Cao et al. (2021) used TI profiling to demonstrate that increased saltiness intensity of NaCl solutions suppressed pungency

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elicited by Sichuan pepper oleoresins. Kostyra et al. (2010) showed that burn intensity evoked by capsaicin was highest in water solutions and decreased in starch gruels, model soups and sauces demonstrating a strong influence of the composition and consistency of the liquid food matrix on oral burn. Other studies demonstrated that burn intensity decreased with dairy protein concentration (Farah et al., 2022; Gøkhan et al., 2023; Nolden et al., 2019). In solid foods such as beef patties, Reinbach and colleagues revealed that increased oral burn suppressed meat flavor (Reinbach et al., 2007; Reinbach et al., 2009).

Temporal Dominance of Sensations (TDS) has been used to investigate the temporal perception of simplified trigeminal stimuli, such as Hydroxyl-Sanshool compound (Zhang et al., 2017), Chinese *Zanthoxylum bungeanum* (Zhang et al., 2018) and habanero peppers (Ramírez-Rivera et al., 2021). He et al. (2021) compared temporal sensory profiles of young and old Baijiu using TDS and showed differences in the temporality of “burning”, “prickle” and “numbing” between young and old Baijiu. Djekic et al. (2021) evaluated the burn perception of pork meat treated with three types of Tabasco hot sauces using TDS and did not observe significant interactions between burn and other sensory perceptions.

Temporal Check-All-That-Apply (TCATA) has been used to explore the temporal sensory perception of huajiao (*Zanthoxylum*) and sanshools (Feng et al., 2023). Pungency sensations appeared in the temporal sequence: tingling, salivating, cooling, and burning, followed by vibrating and numbing. Moss et al. (2023) described the effect of piperine on taste perception of low sodium tomato soups using TCATA, suggesting that saltiness, savory and sweetness were selected less frequently for soups with piperine than for soups without piperine. The effects of piperine on flavor and mouthfeel perceptions were not quantified. Baker et al. (2016) applied TCATA to compare the dynamic perception of Syrah wines differing in ethanol content. High ethanol wines were described more by heat and ethanol burn compared to low ethanol wines. Recently, Pramudya and Seo (2023) used different temporal sensory methods (TI followed by RATA and TCATA) to characterize oral irritation and its subqualities. The study demonstrated that dominant subqualities of capsaicin solutions include burning, stinging/pricking, tingling, and warm/hot. The TCATA analysis revealed that initial perception of the more algogenic sensations (burning, stinging/pricking) lasted for shorter periods, while the milder sensations (tingling, warm/hot) lasted longer. This study therefore demonstrated clearly how TI can be supplemented with TCATA for greater understanding of the temporal dynamics of oral irritation perception. To summarize, the incorporation of trigeminal stimuli causing oral burn in foods impacts dynamic sensory perception.

This study aimed to determine the effect of oral burn on temporal taste, flavor and mouthfeel perception of tomato soups, curried rice and beef patties. The study had two objectives: 1) to compare the temporal oral burn of capsaicin and ground dried chilies at different concentrations in aqueous solution/dispersion and 2) to quantify the impact of oral burn on temporal taste, flavor and mouthfeel perception of three common foods. Capsaicin and ground dried chilies were chosen as trigeminal stimuli since ground dried chilies have high ecological validity as they are commercially available and commonly used in food preparations at home. Furthermore, preliminary sensory testing suggested that the temporality of the oral burn differed between foods containing ground chili pepper and capsaicin. Most published literature has tested the impact of trigeminal irritation caused by capsaicin on associated taste and flavor perception. However, consumers rarely have access to pure capsaicin solutions, so findings may have limited relevance to the consumer experience of consuming chili-based condiments and spices with variable amounts of capsaicin. To test this, the current trial included both pure capsaicin and chili powder for comparison of their impact on taste, texture and flavor perception in complex matrices. Oral burn intensity of capsaicin solutions and ground dried chili dispersions differing in concentrations were characterized using TI profiling. Dynamic sensory perception of complex liquid and solids foods with and without added capsaicin and ground dried chilies were determined using TCATA. We hypothesized that (i) capsaicin solutions and ground dried chili dispersions display distinct dose–response temporal oral burn intensity profiles and that oral burn of ground dry chilies is perceived faster than capsaicin, and (ii) that adding capsaicin or ground dried chilies to tomato soups, curried rice and beef patties leads to a suppression and temporal modification of taste, flavor and mouthfeel perception. We further hypothesized that (iii) oral burn of capsaicin and ground dried chili at different concentrations would have different suppression effects on temporal taste, flavor and mouthfeel perception of three common foods.

2. Materials and methods

2.1. Participants

Seventy-three participants (47 women and 26 men, 27.1 ± 7.3 years, BMI 22.5 ± 3.5 kg/m^2) were recruited from the Wageningen University campus and surroundings using social media and a database of volunteers with an interest in human studies of Wageningen University. Selected participants met the following inclusion criteria: 18–60 years old, having complete dentition, no chewing or swallowing problems, BMI of 18.5–30 kg/m^2, being willing to eat (moderately) spicy foods, no food allergies to any of the foods used in this study, no energy-restricted diet or having a weight change of more than 5 kg in the last two months, not pregnant or intentions to become pregnant, not breastfeeding, not taking any medication that may affect the function of taste, smell, mastication or salivation, and non-smoker. Participants meeting these criteria filled in the chili pepper questionnaire to assess their liking and habitual intake of a variety of foods containing chili peppers (Byrnes & Hayes, 2013, 2016; Choi & Chan, 2015; Lawless et al., 1985; Lyu et al., 2021; Nolden & Hayes, 2017; Reinbach et al., 2007).

Participants’ (n = 73) average intake frequency of foods containing chili pepper was 83 ± 4 times per year and varied substantially across participants with an interquartile range (IQR) of 24–182 times per year. The majority of participants (n = 51) indicated they consumed spicy food two or more times per month, while the minority (n = 22) reported less frequent consumption. Most participants (n = 67) reported to like spicy foods, and 5 participants indicated no preference for spicy foods. Only 1 participant indicated to not like spicy foods. Participants’ ethnicities were self-reported, with the majority of participants endorsing Asian ancestry (n = 41) and Caucasian ancestry (n = 31), and one participant of African ancestry (n = 1). Written informed consent was obtained from all participants. All participants were reimbursed for their participation. The study did not meet the requirements to be reviewed by the Medical Research Ethical Committee of the Netherlands according to the “Medical Research Involving Human Subjects Act” of the Netherlands (WMO in Dutch). The study was conducted in agreement with the ethics regulations laid out in the Declaration of Helsinki (2013).

2.2. Materials

Ground dried chilies (100 % chili pepper, Verstegen Spices & Sauces, batch no.: 9894407) were purchased from a local supermarket (Albert Heijn, Wageningen, the Netherlands). Capsaicin was purchased from Sigma-Aldrich (Sigma#360376; LOT no: MKCN1625; mixture of 65 % capsaicin and 35 % dihydrocapsaicin). The chemical composition of the ground dried chili was not determined. Previously, it has been reported that dried chili powder contains 1,100–28,000 μg/g capsaicin depending on the chili variety used to prepare the dried chili powder (Popelka et al., 2017). Capsaicin has lower ecological validity as it is not a common ingredient used in food preparations at home but the composition is known. Other food ingredients were purchased from the supermarket including minced beef (16 % fat, Albert Heijn), curry paste (Korma, Patak’s), coconut milk (Kokosmelk, Fairtrade Original), indica rice (Pure basmati rice, Tilda), eggs (Albert Heijn), salt (NaCl, LoSalt, Klinge

Foods), wheat flour (Albert Heijn), ground dried garlic powder (Verstegen Spices & Sauces), and tomato soup (Unox Romige Tomaten Soep; Unilever Nederland B.V., Rotterdam). Unsalted crackers (Albert Heijn) were purchased and used as palate cleanser during the sensory evaluations.

2.3. Preparation of capsaicin solutions and chili dispersions for TI-profiling

Capsaicin (CAP) solutions and ground dried chili (CHI) dispersions were prepared for TI evaluations (Table 1) at two concentrations (hereafter 'Low' and 'High'). The concentrations of capsaicin and ground dried chilies used in TI-profiling were estimated in a pilot study, with the intention to obtain two discernably different levels of oral burn intensity (low but clearly noticeable and moderately high oral burn intensity), and to obtain two levels of oral burn intensity that were comparable between chili and capsaicin. In the pilot study, a broad range of concentrations of capsaicin solutions (0.0001–0.002 %) and chili dispersions (0.01–1.0 %) were prepared and rated by 15 participants (9 women and 6 men; participants involved in the pilot study did not participate in the main study) using a general Labeled Magnitude Scale (Bartoshuk et al., 2003; Byrnes & Hayes, 2013; Lyu et al., 2021; Nolden & Hayes, 2017). After the pilot study, dispersions of ground dried chilies (0.1 and 0.3 % w/w) were prepared in plastic medicine cups by dispersing ground dried chilies in 15 g reverse osmosis (RO) water for 60 min while stirring. Dispersions of ground dried chilies were thoroughly stirred before serving. A capsaicin stock solution (0.1 % w/w) was prepared by dissolving 100 mg capsaicin in 10 g of 95 % food-grade ethanol. Capsaicin solutions (0.002 and 0.010 % w/w) were then prepared by diluting the stock solution with RO water to final concentrations. All samples were freshly prepared on the day of the sensory evaluation.

2.4. Preparation of soups, rice and beef patties for TCATA evaluations

Tomato soup, curried rice and beef patty were chosen as they represent commonly consumed staple foods in the Netherlands and elsewhere. These foods were complex enough in their main sensory features to facilitate a comparison of the effect of oral burn on taste, flavor and mouthfeel. Table 1 provides an overview of all foods prepared for the TCATA evaluation. The concentrations of added capsaicin and ground dried chilies were determined in another pilot study, with the intention to obtain three levels of oral burn intensity: control (no burn), low and high burn, and to obtain comparable burn intensities between capsaicin and chili. In the pilot study, a broad range of concentrations of capsaicin (used as a stock solution) and ground dried chilies were added to tomato soup, curried rice and beef patty, and oral burn intensity was rated by 20 participants (13 women and 7 men; participants involved in the pilot study did not participate in the main study) using a general Labeled Magnitude Scale (Bartoshuk et al., 2003; Byrnes & Hayes, 2013; Lyu et al., 2021; Nolden & Hayes, 2017). Sensory attributes to describe tomato soup, curried rice and beef patty were generated by the research team considering previously published sensory studies of these foods (Elzerman et al., 2011; Lyu et al., 2022; Nishida et al., 2021; Reinbach et al., 2007). The attribute lists were refined and modified based on group discussion among the research team and validated in a pilot test using CATA with n = 20 participants. The attributes most frequently selected by the 20 participants in the preliminary study using CATA were included in the final attribute lists for the TCATA evaluation. The list of attributes and their definitions are summarized in Table 2.

All food products were prepared in a food-safe environment in the kitchen of the Human Research Unit of Wageningen University. Prior to the study, all researchers received formal training by the technical staff of the kitchen for food-safe food preparations. Food-safe standard procedures were followed for the preparation of all products. Standardized cooking procedures described by Lyu et al. (2022) were used for sample preparation to ensure consistency. Tomato soups were prepared by adding different amounts of capsaicin stock solution or ground dried chilies to the ready-to-use tomato soup to reach the final concentrations (Table 1), then being mixed and heated in a pan until boiling. Curried rice was prepared by combining coconut milk (70 % w/w) and curry paste (30 % w/w) in a saucepan which was heated over medium–low heat for 5 min, whilst occasionally stirring. Different amounts of capsaicin stock solution and ground dried chilies were added to the sauce after cooling and mixed by hand with a whisk. Indica rice was prepared on the day of the test session by rinsing three times with water and cooking in an electric rice cooker (Russell Hobbs MaxiCook rice cooker, Oldham, UK) with water at a 1:1.9 ratio for 30 min (Ayabe et al.,

Table 1
Overview of solutions and food products used for TI and TCATA evaluations with presentation form and serving temperature.

Sensory evaluation	Samples		Concentration (w/w%)		Presentation form	Serving temperature
			Capsaicin	Dried ground chili		
TI	Capsaicin solution	CAP-Low	0.0002	–	Aqueous solution (15 g) served in a plastic cup	20 °C
		CAP-High	0.0010	–		
	Dried ground chili dispersion	CHI-Low	–	0.10		
		CHI-High	–	0.30		
TCATA	Tomato soup	Control	–	–	Soup (15 g) served in a plastic cup	60 °C
		CAP-Low	0.005	–		
		CAP-High	0.015	–		
		CHI-Low	–	0.10		
		CHI-High	–	0.80		
	Curried rice	Control	–	–	Rice (10 g) served on an aluminum dish	60 °C
		CAP-Low	0.004	–		
		CAP-High	0.006	–		
		CHI-Low	–	0.75		
		CHI-High	–	2.25		
	Beef patty	Control	–	–	Patty cube (7 g; 1.0×1.0×1.0 cm) served on an aluminum dish	60 °C
		CAP-Low	0.004	–		
		CAP-High	0.006	–		
		CHI-Low	–	2.00		
		CHI-High	–	4.00		

Table 2
Sensory attributes with definitions used for the TCATA evaluation. Different attribute lists were used for the evaluation of tomato soup, curried rice and beef patty.

Sensory attribute	Definition	Tomato soup	Curried rice	Beef patty
Trigeminal				
Burn	Oral burn perceived in mouth and throat	X	X	X
Taste				
Sweetness	Sensation of basic sweet taste	X	X	
Sourness	Sensation of basic sour taste	X		
Saltiness	Sensation of basic salty taste	X	X	X
Flavor				
Beef flavor	Distinctive taste of beef			X
Coconut flavor	Distinctive taste of curry		X	
Garlic flavor	Distinctive taste of garlic			X
Rice flavor	Distinctive taste of rice		X	
Tomato flavor	Distinctive taste of tomato	X		
Mouthfeel				
Hardness	Force required to bite through the sample with the teeth		X	X
Thickness	Ease to deform the food between tongue and palate and perceived resistance to flow	X		
Graininess	Presence of particles in the mouth, perceived inhomogeneity		X	X
Juiciness	Presence of liquid in the mouth			X
Fattiness	Amount of fat that is perceived when having the sample in the mouth for several seconds			X
Chewiness	Need to chew or difficulty to chew		X	X
Creaminess	Sensation of thick, smooth, velvety mouth-feel	X	X	

2009). Cooked rice was mixed with the curry sauce at a 3:2 wt ratio. The beef patty consisted of minced beef (75 %), water (9 %), salt (1 %), eggs (10 %), flour (3 %), and ground dried garlic powder (2 %). Minced beef was mixed with salt for 30 s at speed 2 in a mixer (Bosch MFQ2600, Stuttgart, Germany). Different amounts of capsaicin stock solution and ground dried chili pepper powder were added and mixed for 60 s at speed 2. The remaining ingredients were added and mixed for 90 s at speed 3. Each raw beef patty (150 g) was formed using a hamburger patty maker (diameter: 11 cm; height: 1.5 cm) to ensure uniformity. The patties were stored at − 20 °C immediately after preparation. On the day of each session, patties were thawed for 1 h at room temperature and then roasted at 200 °C for 10 min on each side in a universal combi-oven (Self Cooking Center, SCCWE61G. RationalAG, LandsbergamLech, Germany). After roasting, beef patties were cut into cubes of 1.0 × 1.0 × 1.0 cm. Serving sizes were adjusted to allow for sensory evaluations using single bites (15 g tomato soup served in a plastic medicine cup, 10 g curried rice served on an aluminum dish, and 7 g beef patty cube served on an aluminum dish). All samples were labeled with random 3-digit codes and were kept warm in a water bath (60 °C) before the TCATA evaluation.

2.5. Experimental procedure

Data collection comprised one familiarization session and four test sessions (1 TI and 3 TCATA test sessions), which were conducted in the sensory booths of the Department of Human Nutrition and Health at Wageningen University. All participants were asked not to smoke, eat spicy food or drink caffeinated beverages for a minimum of 2 h before the sessions. On the day of the scheduled test session, participants were asked if they had any remaining questions about the methodology and the attribute lists that they received. Participants were then seated individually in sensory booths and were provided with the list of attributes and their definitions. Data collection of TI and TCATA was performed with Compusense® Cloud (Compusense Inc., Guelph, Ontario, Canada). During each test session, a 2.5 min break was enforced to cleanse the palate thoroughly with crackers and water between sample evaluations (Lyu et al., 2021; Nasrawi & Pangborn, 1990b; Nolden & Hayes, 2017). At the end of the 2.5 min break, participants were asked if they still perceived oral burn (“yes” or “no”). Participants were given additional time to cleanse their mouths when they answered the question with “yes” indicating that they still perceived oral burn.

2.5.1. Familiarization session

One familiarization session of 30 min was used to acquaint participants with the definitions of sensory attributes (Table 2), the TCATA and TI methodology, and the Compusense® Cloud software used for data collection. The TCATA approach features participants selecting attributes that are applicable in describing the sample tested. TCATA attribute selection was made transient by a process of automatic fading attributes whereby selected attributes gradually become unselected over a predefined period of 8 s (Ares et al., 2016; Castura et al., 2016). During the familiarization session, participants were familiarized with the TI method using a 0.001 % w/w capsaicin solution and with the TCATA method using control tomato soup, curried rice and beef patty. After the familiarization session, participants reported that it was clear to them how to perform the test in the evaluation session. Prior to the start of the test sessions, participants were asked if the procedure was still clear and explained again if necessary.

2.5.2. Time-Intensity evaluation(TI)

During one test session of 60 min, the burn intensity of capsaicin solutions and ground dried chili dispersions were assessed over a time period of 120 s using Compusense® Cloud. Participants (n = 73) received samples in two blocks (Block 1 and 2; each block consisting of 4 samples: CHI-Low dispersion, CAP-Low solution, CHI-Low dispersion and CAP-High dispersion) so that a total of eight TI evaluations were carried out in one session. Each sample was evaluated in duplicate by each participant. Within a block, participants received samples in a fixed order of ascending burn to help minimize potential desensitization (Green, 2001; RentmeisterBryant & Green, 1997). Block 1 started with CHI-Low dispersion, followed by CAP-Low solution, CHI-High dispersion, and CAP-High solution. Block 2 started with CAP-Low solution, followed by CHI-Low dispersion, CAP-High solution, and CHI-High dispersion. The order of the blocks was counterbalanced across participants. During the evaluation, participants were instructed to take the whole sample (15 g) into their mouths and swallow, starting with oral burn intensity “0″ and then moving the cursor on a horizontal continuous line scale as the intensity of oral burn changed in mouth, and coming back to ‘0’ when the oral burn was not perceived anymore. The scale was anchored at the ends with ‘0 (no burn at all)’ and ‘100 (very strong burn)’. Data were recorded at a frequency of 5 s for 120 s.

2.5.3. Temporal Check- All-That-Apply evaluation(TCATA)

Three TCATA sessions of 60 min each were conducted on three separate days. Three foods were separately presented so that tomato soups were presented in one session, curried rice in another session, and beef patties in another session. Within a session, participants received samples in two blocks (Block 1 and 2; each block consisted of 5 samples: Control, CHI-Low, CAP-Low, CHI-Low and CAP-High food) so that participants evaluated each sample in duplicate in a session. Within a block, participants received samples in a fixed order of ascending burn to minimize potential desensitization. Block 1 started with control, followed by CHI-Low, CAP-Low, CHI-High and CAP-High food. Block 2 started with control, followed by CAP-Low, CHI-Low, CAP-High and

CHI-High food. The order of the sessions and blocks was randomized and counterbalanced across participants to mitigate the impact of potential response bias and carryover effects.

During the TCATA-fading evaluation, participants were instructed to click a "Start" button concurrently with putting the sample into the mouth and to immediately commence tracking changes in the food product sample by checking and unchecking attributes, such that the attributes that were selected described the perception of the food at that moment. All attributes were presented in a three-column format on the computer screen. The order position of attributes was randomized across assessors, but the order remained consistent for a given assessor (Meyners & Castura, 2016). At any time between clicking "Start" and the end of the evaluation time after 80 s, participants were free to check the attributes that apply to describe the sensory characteristics of the sample at each moment and to uncheck the terms when they no longer apply to describe the sample. In a TCATA-fading evaluation, some attributes may be never checked, other attributes are checked but never unchecked, and other attributes are checked and unchecked one or more times, ending in either the checked or the not checked state. Multiple attributes can be selected simultaneously according to when the attribute is considered applicable to describe the sample. Participants can only select attributes actively and selected attributes automatically fade gradually over a predefined period of 8 s based on previous approaches (Ares et al., 2016; Castura et al., 2016). Participants were required to click a "Swallow" button to indicate the swallowing time when they naturally swallowed the food. TCATA-fading data collection was stopped automatically 80 s after participants clicked the start button.

2.6. Statistical data analysis

TI and TCATA data were exported from Compusense® Cloud and pre-processed in Microsoft Excel (Microsoft, Inc., Belleview, WA, USA). For each temporal method, normality tests were completed to confirm the normality of data distribution and reliability of replicate results, and an average was taken for further analysis. All statistical analyses were performed using R studio (v4.1.2; R Core Team 2021).

2.6.1. TI analyses

TI curves were determined by averaging the data at each point of time across participants and replicates. For each TI curve, the maximum intensity (I_{max}), the time at which the maximum intensity occurs (T_{max}), and the total area under the curve (AUC) were extracted. To facilitate relative comparisons across samples, TI data were normalized on I_{max} by expressing an individual's burn rating (I) at any time point as a fraction of the maximum burn intensity (I_{max}) (Normalized burn intensity (%) = I/I_{max} x 100). $T_{50\%max}$ was extracted from the normalized TI curves, representing the period after which the normalized burn intensity decreased from its maximum intensity (100 %) to half its intensity (50 %). TI parameters were individually analyzed and differences between samples were assessed by ANOVA followed by Tukey's test using a significance level of $p < 0.05$.

2.6.2. TCATA analyses

TCATA data were analyzed following the recommendations provided by Castura et al. (2016). Temporal curves were constructed using the tempR package with the R-software version 4.2.1 (R Core Team 2022). For each food category, citation proportions for each attribute were calculated as the proportion of participants who checked a given attribute at any given moment (every 0.1 s) during the evaluation period (80 s). Averages were derived across all participants and replicates to produce a single temporal curve for each food product and its attributes. For each product group (tomato soup, curried rice and beef patty), the citation proportions of the control sample (food without chili/capsaicin) were compared to the citation proportions of the corresponding test samples (food products with low/high chili/capsaicin). Significant differences in TCATA profiles between the control sample and test sample were calculated for each time point and each attribute by applying two-sided Fisher–Irwin tests to evaluate whether citation proportions for the pairs of products were significantly different at $p < 0.05$ (Castura et al., 2016). For a better visualization, smoothing of TCATA curves was performed using the smooth function of the tempR package of R-software version 4.2.1. Highlighted sections (bold lines) in the TCATA curves represent periods during which significant differences between test samples and control samples were observed ($p < 0.05$).

For each product group and each attribute, TCATA parameters including the area under the citation proportion curve (AUC), the maximum citation proportions (Cit_{max}), the time to reach maximum citation proportion (T_{max}), and the time period at which the citation proportion declined to half of the maximum citation proportion ($T_{½max}$) were extracted from the TCATA curves. TCATA parameters were individually analyzed and differences between samples were assessed by ANOVA followed by Tukey's test using a significance level of $p < 0.05$.

3. Results

3.1. Temporal oral burn of capsaicin solutions and ground dried chili pepper powder dispersions (TI profiling)

The changes in burn intensity over time of capsaicin (CAP-Low/High) solutions and ground dried chili (CHI-Low/High) dispersions are illustrated in Fig. 1a and the corresponding TI parameters are summarized in Table 3. As expected, maximum burn intensity I_{max} significantly increased with increasing concentration of the trigeminal stimuli. Burn intensity was the highest for CHI-High followed by CAP-High and CHI-Low and was the lowest for CAP-Low. Area under curve (AUC) followed approximately a similar trend as I_{max}. The time to reach the maximum intensity of burn was not significantly affected by concentration and type of trigeminal stimulus. The time period after which the normalized burn intensity (see section 2.4.1) decreased from its maximum intensity to half its intensity ($T_{50\%max}$; Fig. 1b) depended strongly on concentration and type of trigeminal stimulus. The longest $T_{50\%max}$ was observed in the CAP-High solution, while the shortest $T_{50\%max}$ was found in the CAP-Low solution and CHI-Low dispersion. Burn lasted significantly longer for the higher concentration capsaicin solutions than higher concentration ground dried chili dispersions. $T_{50\%max}$ depended on the oral burn intensity with higher oral burn causing longer-lasting burn. $T_{50\%max}$ increased by 30 s between CAP-Low and CAP-High solutions and by 19 s between CHI-Low and CHI-High dispersions.

3.2. Impact of capsaicin and ground dried chili pepper on dynamic sensory perception of tomato soups

3.2.1. Effect of chili/capsaicin addition on burn of tomato soups

Fig. 2a and Fig. 3 show the TCATA curves for tomato soups. Table 4 and 5 summarize and compare the parameters extracted from the TCATA curves for tomato soups. Control tomato soup (Fig. 2a) had the lowest citation proportion for burn with a maximum citation proportion of 0.097. Significant differences in the citation proportions of burn were found with the addition of capsaicin and chili to tomato soup throughout the entire evaluation period, suggesting that addition of capsaicin and ground dried chili resulted in a dynamic and long-lasting burn (Fig. 2a, bold lines). At the beginning of the evaluation (<5 s), TCATA profiles of burn for CAP-Low/High tomato soup were similar to CHI-Low tomato soup (Fig. 2a). Later in the evaluation (>5 s), TCATA profiles of burn evolved differently between capsaicin and dried ground chili in tomato soups. The citation proportion of burn surpassed that of other sensory attributes after the swallowing moment at around 22 s for CAP-Low tomato soup (Fig. 3b) and at around 18 s for CAP-High tomato soup (Fig. 3c), whereas the citation proportion of burn exceeded that of other sensory attributes before the swallowing moment at around 14 s for CHI-Low tomato soup (Fig. 3d) and at around 5 s for CHI-High beef patty

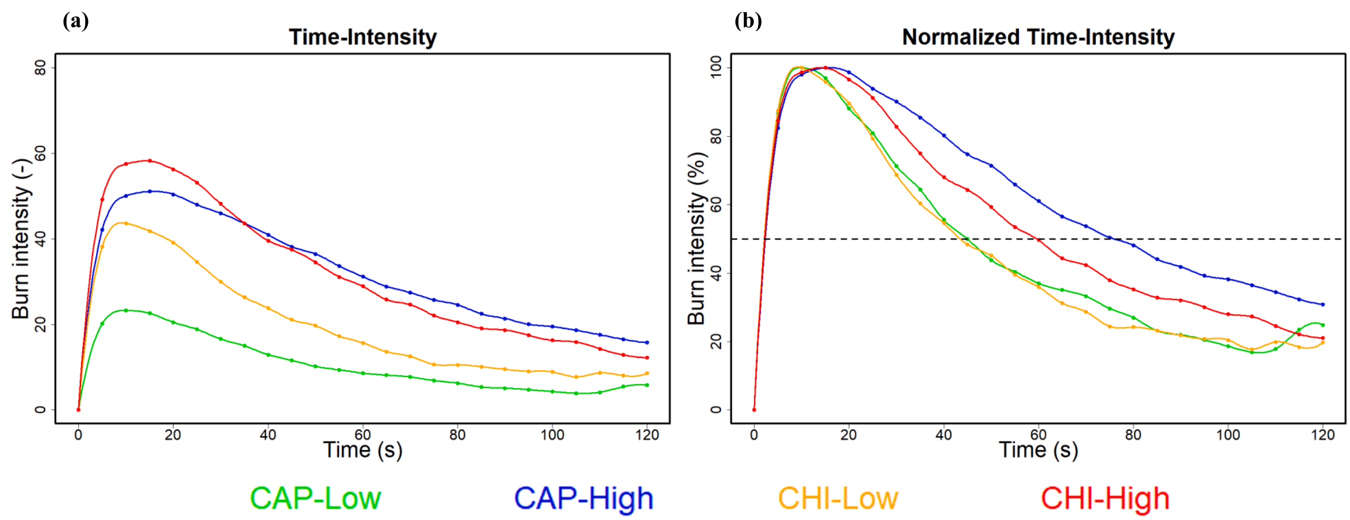

Fig. 1. (a) Average Time-Intensity profiles (n = 73, duplicate) and (b) Time-Intensity profiles normalized on maximum intensity of capsaicin (CAP) and chili (CHI) solutions differing in concentration (Low, High). The dashed black line corresponds to the normalized burn intensity of 50 % to indicate the half-time at which the normalized burn intensity declined from 100 to 50 % ($T_{50\%max}$).

Table 3
Parameters extracted from the Time-Intensity profiles (n = 73, duplicate) of capsaicin (CAP) solutions and dried ground chili (CHI) dispersions differing in concentration (Low, High) are shown (mean with standard deviation (SD)) with F- and p-values. Different superscript letters indicate significant differences ($p < 0.05$) between samples. I_{max} represents the maximum oral burn intensity; T_{max} represents the time when oral burn reached I_{max}; AUC is the area under the TI curve and $T_{50\%max}$ represents the period after which the normalized burn intensity decreased from its maximum intensity (100 %) to half its intensity (50 %).

Samples	I_{max} (-)	T_{max} (s)	AUC (-)	$T_{50\%max}$ (s)
CAP-Low	23 ± 2[a]	16 ± 1	1276 ± 152[a]	45 ± 2[a]
CAP-High	51 ± 3[b]	16 ± 1	3813 ± 275[c]	75 ± 4[c]
CHI-Low	44 ± 2[b]	19 ± 2	2327 ± 182[b]	43 ± 3[a]
CHI-High	58 ± 3[c]	16 ± 1	3759 ± 224[c]	62 ± 3[b]
F-value	34.4	0.7	29.7	15.8
p-value	<0.001	0.58	<0.001	<0.001

(Fig. 3e).

Relative to control, the maximum citation proportion (Cit_{max}) of burn significantly ($p < 0.05$) increased by 0.619 peaking at 22 s for CAP-Low tomato soup and by 0.664 peaking at 25 s for CAP-High tomato soup (Table 4 and 5). Similarly, Cit_{max} of burn significantly ($p < 0.05$) increased by 0.709 peaking at 19 s for CHI-Low tomato soup and by 0.873 peaking at 30 s for CHI-High tomato soup relative to control (Table 4 and 5). Area under the curve (AUC) of burn differed significantly ($p < 0.001$) among tomato soups and was the largest for CHI-High tomato soup, which was significantly higher than those of the other tomato soups suggesting that high concentrations of chili led to a strong and long-lasting burn. CHI-Low and CAP-High tomato soup had relatively similar burn temporal characteristics with similar AUCs (Table 4). CAP-Low tomato soup was the most different compared to the other tomato soups mainly due to its lowest values of AUC, $Cit_{max,}$ and T_{max}. Maximum burn perception of CAP-High was reached significantly earlier than for CHI-High in tomato soups (Table 4) indicating that the build up of oral burn in tomato soups was faster for capsaicin than for ground dried chili when burn intensity was high.

3.2.2. Effect of burn on taste, flavor and mouthfeel perception of tomato soups

Control tomato soup (Fig. 3a, Table 4 and 5) had the highest citation proportion for tomato flavor with a Cit_{max} of 0.933 and creaminess with a Cit_{max} of 0.903 peaking at 10 s, followed by sourness with a Cit_{max} of 0.679 peaking at 12 s and sweetness with a Cit_{max} of 0.582 peaking at 11 s. Relative to control tomato soup, significant differences in the citation proportions of sweetness, sourness, tomato flavor and creaminess were found with the addition of capsaicin (Fig. 2b-2c) and ground dried chili (Fig. 2d-2e) to tomato soup throughout the entire evaluation process, suggesting burn significantly suppressed dynamic sensory perception of sweetness, sourness, tomato flavor and creaminess for both trigeminal stimuli. At the beginning of the evaluation, the temporal sensory profile of CAP-Low/High tomato soup (Fig. 3b-3c) was similar to that of CHI-Low tomato soup (Fig. 3d) with the perception of tomato flavor having the highest citation proportion, while the sensory profile of CHI-High tomato soup displayed differences with the perception of burn having the highest citation proportion. Consistently, sourness of CAP-Low/High (Fig. 3b-3c) and CHI-Low tomato soup (Fig. 3d) was less perceived with a shorter period (<10 s) of significant difference compared to that of CHI-High tomato soup (Fig. 3e). Next, sweetness, sourness, tomato flavor and creaminess of CAP-Low/High tomato soup (Fig. 3b-3c) and CHI-Low/High tomato soup (Fig. 3d-3e) were perceived as less intense after swallowing but with a long period (>15 s) during which they were significantly different from control tomato soup. Overall, sweetness, sourness, tomato flavor and creaminess showed a significant decrease in perception for longer time periods of the evaluation. After swallowing, the citation proportion of burn was still high but the citation proportions of other sensory attributes gradually reduced until the end of the evaluation.

Compared to control tomato soup, AUC values of CAP-Low/High and CHI-Low/High tomato soup significantly ($p < 0.05$) decreased by up to 65 % for sweetness, by up to 26 % for sourness, by up to 37 % for tomato flavor, and by up to 37 % for creaminess, respectively (Table 4 and 5). Similarly, Cit_{max} of CAP-Low/High and CHI-Low/High tomato soup significantly ($p < 0.05$) decreased by up to 58 % for sweetness and by up to 13 % for tomato flavor (Table 4 and 5). Apart from burn, T_{max} of other sensory attributes did not differ ($p > 0.05$) among tomato soups (Table 4 and 5). With the addition of capsaicin or ground dried chili, the maximum decrease in $T_{½max}$ that was observed in the of CAP-Low/High and CHI-Low/High tomato soups: $T_{½max}$ significantly decreased by up to 36 % for sweetness and tomato flavor, by up to 22 % for sourness and by up to 34 % for creaminess respectively compared to control tomato soup (Table 4 and 5). The oral burn evoked by capsaicin and chili suppressed the perception of sweetness, sourness, tomato flavor and creaminess in tomato soup and shortened the these attributes perception after

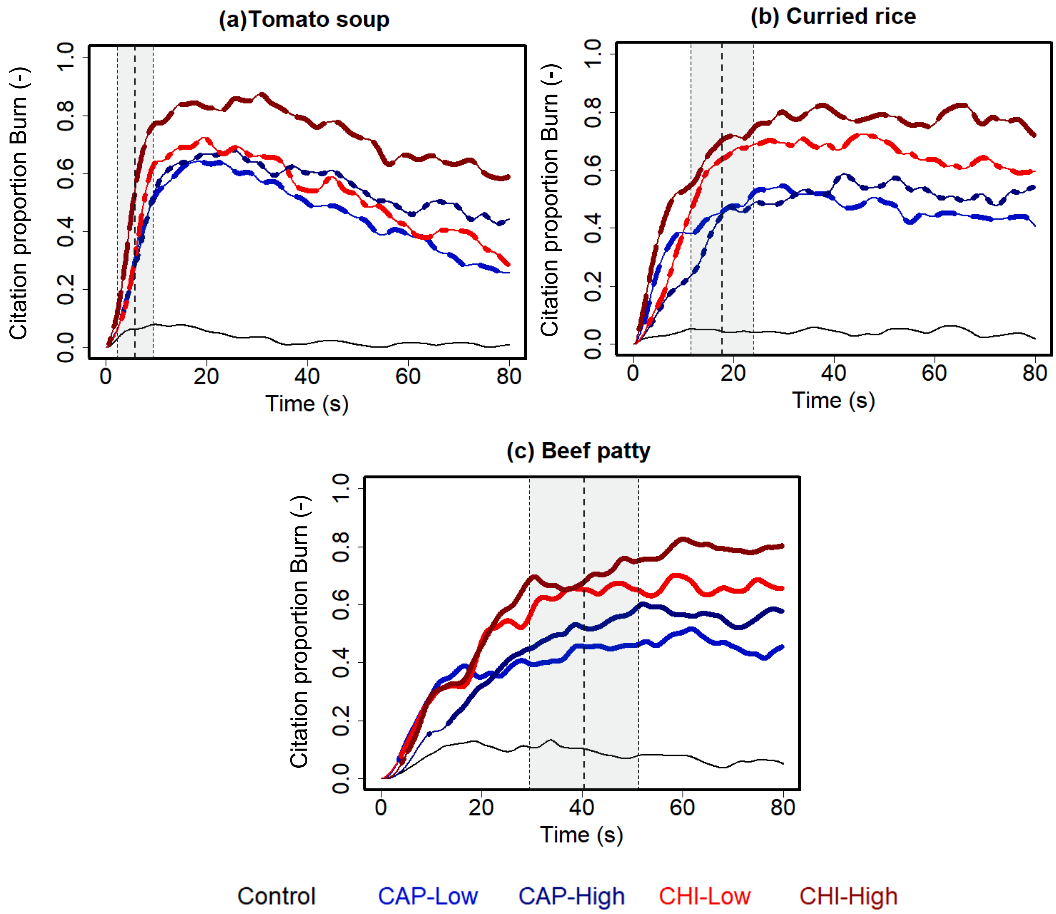

Fig. 2. TCATA curves (n = 73, duplicate) of burn of (a) tomato soup, (b) curried rice and (c) beef patty with added capsaicin (CAP) and dried ground chili (CHI) at low and high concentrations (Low, High). Highlighted bold sections indicate significant ($p < 0.05$) differences in citation proportions of burn at that evaluation moment compared to the control. The legend indicates the color coding of the samples. Vertical dotted lines represent the average swallowing moment across each food product and the grey area represents the standard deviation.

swallowing.

3.3. Impact of capsaicin and chili pepper on dynamic sensory perception of curried rice

3.3.1. Effect of chili/capsaicin addition on burn of curried rice

Fig. 2b and Fig. 4 show the TCATA curves for curried rice. Table 4 and 5 summarize and compare the parameters extracted from the TCATA curves for curried rice. Control curried rice (Fig. 2b) had the lowest citation proportion for burn with a Cit_{max} of 0.062. Significant differences in the citation proportions of burn were found with the addition of capsaicin and ground dried chili to curried rice throughout the entire evaluation process, suggesting that added capsaicin and ground dried chili resulted in a dynamic and long-lasting burn (Fig. 2b, bold lines). At the beginning of the evaluation (<10 s), TCATA profiles of burn for CHI-High curried rice showed a higher citation proportion for burn (Fig. 2b). Later in the evaluation (>10 s), TCATA profiles of burn displayed differences between CAP-Low/High and CHI-Low/High curried rice: the citation proportion of burn surpassed that of other sensory attributes after swallowing at around 20 s for CAP-Low curried rice (Fig. 4b) and at around 19 s for CAP-High curried rice (Fig. 4c), whereas the citation proportion of burn exceeded that of other sensory attributes before swallowing at around 14 s for CHI-Low curried rice (Fig. 4d) and at around 11 s for CHI-High curried rice (Fig. 4e).

Relative to control, the maximum citation proportion of burn significantly ($p < 0.001$) increased by 0.506 peaking at 30 s for CAP-Low curried rice and by 0.541 peaking at 45 s for CAP-High curried rice (Table 4 and 5). Similarly, Cit_{max} of burn significantly ($p < 0.001$) increased by 0.671 peaking at 42 s for CHI-Low curried rice and by 0.774 peaking at 30 s for CHI-High curried rice (Table 4 and 5). Areas under the curve (AUCs) of burn differed significantly ($p < 0.001$) among curried rice and displayed the largest AUC value for CHI-High curried rice, which was significantly higher than those of the other curried rice suggesting that a higher concentration of chili led to a strong and long-lasting burn. The addition of ground dried chili to curried rice led to a larger AUC of burn compared to the addition of capsaicin. Maximum burn perception of CHI-High was reached significantly earlier than for CAP-High in curried rice (Table 4) indicating that the build up of oral burn in curried rice was faster for ground dried chili than for capsaicin when burn intensity was high.

3.3.2. Effect of burn on taste, flavor and mouthfeel perception of curried rice

Control curried rice (Fig. 4a) was characterized by coconut flavor reaching its maximum citation proportion (0.685) at 10 s, followed by rice flavor with maximum citation proportion of 0.575 at 15 s, sweetness with maximum citation proportion of 0.548 peaking at 11 s, and graininess with maximum citation proportion of 0.527 at 14 s. The end of the evaluation of control curried rice was characterized by high citation proportions of coconut flavor. Compared to control curried rice, significant differences in the citation proportions of sweetness, coconut flavor, rice flavor and creaminess were found with the addition of

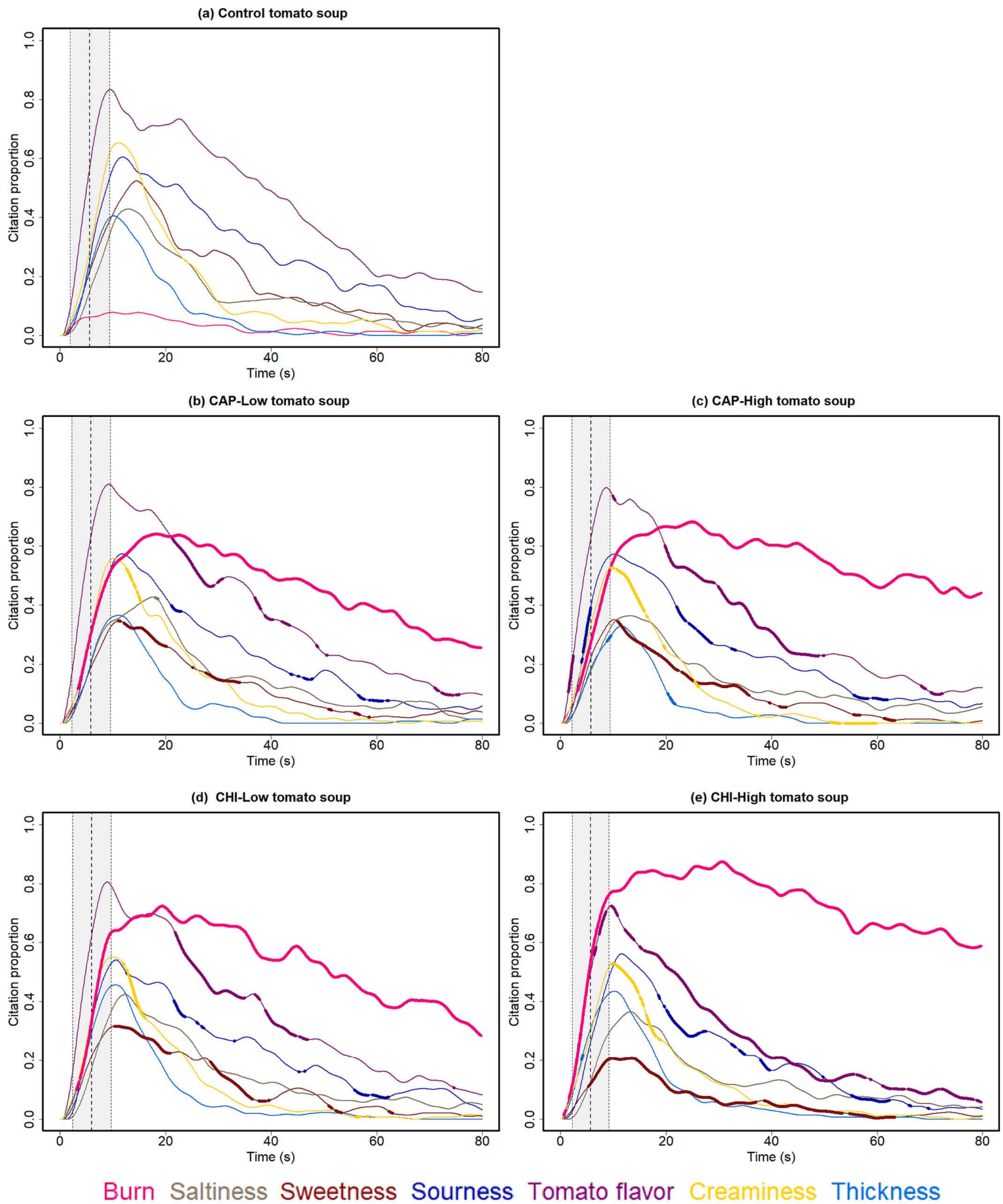

Fig. 3. TCATA curves (n = 73, duplicate) of (a) tomato soup without capsaicin/chili (control) and (b-c) tomato soup with added capsaicin (CAP) at low (b) and high (c) concentrations and (d-e) tomato soup with added dried ground chili (CHI) at low (d) and high (e) concentration. Solid lines represent citation proportions for each sensory attribute. Highlighted bold sections indicate significant ($p < 0.05$) differences in citation proportions of an attribute during a time interval compared to the control tomato soup. Vertical dotted lines represent the average swallowing moment and the grey area represents the standard deviation. The legend indicates the color coding of the sensory attribute.

capsaicin (Fig. 4b-4c) and chili (Fig. 4d-4e) to curried rice throughout the entire evaluation period, suggesting that burn significantly suppressed dynamic sensory perception of these attributes for both trigeminal stimuli. At the beginning of the evaluation, the temporal sensory profile of CAP-Low/High curried rice (Fig. 4b-4c) was very similar to that of CHI-Low curried rice (Fig. 4d) with the perception of coconut flavor having the highest citation proportion, while the temporal sensory profile of CHI-High curried rice displayed differently with the perception of burn having the highest citation proportion. Consistently, rice flavor of CAP-Low/High (Fig. 4b-4c) and CHI-Low curried rice (Fig. 4d) was less perceived with a shorter period (<10 s) of significant difference compared to that of CHI-High curried rice (Fig. 4e). Next, coconut flavor, sweetness and creaminess of CAP-Low/High curried rice (Fig. 4b-4c) and CHI-Low/High curried rice (Fig. 4d-4e) were less perceived after swallowing but with a long period (>15 s) during which they were significantly different from control curried rice. Overall, sweetness, coconut flavor and creaminess showed a decrease in perception with long significantly different periods of the evaluation. After swallowing, the citation proportion of burn was still kept at a high level but the citation proportion of other sensory attributes gradually reduced until the end of the evaluation.

TCATA parameters extracted from the TCATA curves of curried rice are summarized in Table 4. Relative to control curried rice, AUC values of CAP-Low/High and CHI-Low/High curried rice significantly ($p < 0.05$) decreased by up to 48 % for sweetness, by up to 62 % for coconut flavor, by up to 36 % for rice flavor and by up to 52 % for creaminess

Table 4

Parameters extracted from the TCATA curves (n = 73, duplicate) of tomato soups, curried rice and beef patties. AUC represents the area under the TCATA curve of an attribute, Cit_{max} is the maximum citation proportion of an attribute, T_{max} is the time moment when the maximum citation proportion was reached and $T_{½max}$ is the time period after which the citation proportion decreased to half of the maximum citation proportion. † indicates that citation proportion of an attribute did not decrease to half of the maximum citation proportion. Parameters with significant differences ($p < 0.05$) are highlighted in bold. Different superscript letters indicate significant differences ($p < 0.05$) between samples.

	AUC (-)					Cit_{max}(-)					T_{max} (s)					$T_{½max}$ (s)				
	Control	CAP-Low	CAP-High	CHI-Low	CHI-High	Control	CAP-Low	CAP-High	CHI-Low	CHI-High	Control	CAP-Low	CAP-High	CHI-Low	CHI-High	Control	CAP-Low	CAP-High	CHI-Low	CHI-High
Tomato soup																				
Burn	**2.4**^{a}	**38.4**^{b}	**45.5**^{b}	**43.8**^{b}	**61.0**^{c}	**0.097**^{a}	**0.716**^{b}	**0.761**^{b}	**0.806**^{b}	**0.970**^{c}	**10**^{a}	**22**^{b}	**25**^{b}	**19**^{b}	**30**^{c}	-†	-†	-†	-†	-†
Saltiness	12.2	13.2	11.9	12.9	11.4	0.478	0.478	0.403	0.470	0.410	13	19	11	13	13	25	26	28	28	23
Sweetness	**15.7**^{a}	**10.5**^{b}	**9.0**^{b}	**10.0**^{b}	**5.5**^{c}	**0.582**^{a}	**0.388**^{b}	**0.388**^{b}	**0.358**^{b}	**0.246**^{c}	11	11	10	10	14	**33**^{a}	**28**^{a}	**23**^{b}	**23**^{b}	**21**^{b}
Sourness	**23.6**^{a}	**19.3**^{b}	**20.1**^{b}	**19.6**^{b}	**17.5**^{b}	0.679	0.649	0.634	0.619	0.634	12	12	10	11	11	**36**^{a}	**33**^{a}	**28**^{b}	**28**^{b}	**30**^{b}
Tomato flavor	**38.0**^{a}	**32.5**^{b}	**30.5**^{b}	**31.2**^{b}	**23.9**^{c}	**0.933**^{a}	**0.910**^{a}	**0.888**^{b}	**0.888**^{b}	**0.813**^{b}	10	10	9	9	9	**45**^{a}	**37**^{b}	**35**^{b}	**35**^{b}	**29**^{c}
Creaminess	**36.7**^{a}	**31.5**^{b}	**29.5**^{b}	**30.1**^{b}	**23.0**^{c}	0.903	0.873	0.858	0.858	0.769	10	10	9	9	9	**44**^{a}	**37**^{b}	**35**^{b}	**35**^{b}	**29**^{c}
Thickness	7.0	6.2	5.3	7.5	7.7	0.448	0.403	0.396	0.500	0.485	10	9	11	9	9	18	19	18	18	18
Curried rice																				
Burn	**3.2**^{a}	**35.0**^{b}	**35.8**^{b}	**47.0**^{c}	**55.8**^{d}	**0.062**^{a}	**0.568**^{b}	**0.603**^{b}	**0.733**^{c}	**0.836**^{d}	**35**^{a}	**30**^{a}	**45**^{b}	**42**^{b}	**38**^{b}	-†	-†	-†	-†	-†
Saltiness	3.4	3.8	4.6	4.2	5.3	0.196	0.137	0.171	0.144	0.240	**18**^{a}	**12**^{b}	**12**^{b}	**14**^{b}	**11**^{b}	23	25	24	28	17
Sweetness	**21.2**^{a}	**13.0**^{b}	**13.4**^{b}	**15.2**^{b}	**11.1**^{b}	**0.548**^{a}	**0.425**^{b}	**0.466**^{b}	**0.479**^{b}	**0.404**^{b}	11	9	10	9	9	**42**^{a}	**31**^{b}	**25**^{c}	**35**^{b}	**24**^{c}
Rice flavor	**23.3**^{a}	**20.7**^{a}	**18.6**^{b}	**19.7**^{b}	**14.8**^{c}	**0.575**^{a}	**0.527**^{b}	**0.507**^{b}	**0.575**^{b}	**0.459**^{c}	15	13	10	10	10	**43**^{a}	**43**^{a}	**39**^{ab}	**34**^{b}	**34**^{b}
Coconut flavor	**29.4**^{a}	**22.0**^{b}	**22.1**^{b}	**19.1**^{b}	**11.1**^{c}	**0.685**^{a}	**0.610**^{b}	**0.610**^{b}	**0.541**^{b}	**0.404**^{c}	10	9	9	9	9	**45**^{a}	**35**^{b}	**40**^{ab}	**33**^{b}	**24**^{c}
Creaminess	**12.6**^{a}	**8.9**^{b}	**8.8**^{b}	**8.2**^{b}	**6.0**^{c}	**0.432** ^{a}	**0.342**^{b}	**0.336**^{b}	**0.349**^{b}	**0.240**^{c}	**12**^{a}	**12**^{a}	**12**^{a}	**10**^{a}	**18**^{b}	27	32	30	27	29
Hardness	4.8	4.4	5.3	4.7	5.1	0.247	0.226	0.240	0.226	0.233	11	12	13	11	15	**41**^{a}	**25**^{b}	**25**^{b}	**26**^{b}	**28**^{b}
Chewiness	8.2	8.4	8.3	8.2	9.4	0.336	0.370	0.363	0.349	0.425	9	10	12	11	14	26	26	28	29	31
Graininess	14.6	14.2	13.9	13.8	13.8	0.527	0.555	0.555	0.527	0.568	14	11	13	13	11	32	30	28	28	26
Beef patty																				
Burn	**6.4**^{a}	**31.3**^{b}	**34.2**^{b}	**42.6**^{c}	**47.9**^{c}	**0.147**^{a}	**0.533**^{b}	**0.627**^{b}	**0.713**^{c}	**0.847**^{d}	**34**^{a}	**62**^{b}	**52**^{b}	**58**^{b}	**60**^{b}	-†	-†	-†	-†	-†
Saltiness	22.9	23.0	23.6	19.8	19.6	0.480	0.447	0.540	0.427	0.413	37	26	22	15	31	57	65	54	57	57
Beef flavor	**42.4**^{a}	**38.3**^{ab}	**36.9**^{ab}	**34.8**^{b}	**31.7**^{b}	**0.747**^{a}	**0.700**^{ab}	**0.687**^{b}	**0.653**^{b}	**0.647**^{b}	**9**^{a}	**11**^{a}	**11**^{a}	**15**^{b}	**17**^{b}	**68**^{a}	**66**^{a}	**63**^{ab}	**53**^{b}	**58**^{b}
Garlic flavor	**25.8**^{a}	**23.1**^{a}	**22.9**^{ab}	**18.3**^{b}	**16.3**^{b}	**0.500**^{a}	**0.507**^{a}	**0.480**^{ab}	**0.427**^{b}	**0.353**^{c}	17	26	14	12	19	53	54	57	53	52
Hardness	9.6	10.1	8.2	10.9	8.8	0.320	0.360	0.380	0.420	0.347	9	9	8	9	9	**29**^{a}	**22**^{ab}	**19**^{b}	**29**^{a}	**21**^{b}
Chewiness	21.0	22.4	21.2	21.3	22.5	0.527	0.553	0.627	0.540	0.627	26	20	22	21	21	43	46	41	43	39
Graininess	15.5	15.5	15.9	14.0	13.3	0.407	0.380	0.393	0.387	0.373	15	17	26	23	21	43	44	48	43	42
Juiciness	13.9	12.3	12.2	10.0	10.4	0.360	0.353	0.333	0.267	0.267	23	25	22	20	30	48	38	49	48	48
Fattiness	12.6	10.8	11.1	8.2	9.7	**0.320**^{a}	**0.313**^{a}	**0.327**^{a}	**0.207**^{b}	**0.227**^{b}	**32**^{a}	**21**^{b}	**11**^{c}	**25**^{b}	**15**^{c}	**57**^{a}	**34**^{c}	**38**^{c}	**37**^{c}	**49**^{b}

Table 5
Effects of capsaicin and chili addition to tomato soups, curried rice and beef patties and their interaction effects (one-way ANOVAs) on AUC, Cit_{max}, T_{max} and $T_{½max}$ values obtained from TCATA curves with F- and p-values. AUC represents the area under the TCATA curve of an attribute, Cit_{max} is the maximum citation proportion of an attribute, T_{max} is the time moment when the maximum citation proportion was reached and $T_{½max}$ is the time period after which the citation proportion decreased to half of the maximum citation proportion. TCATA parameters with significant differences ($p < 0.05$) are highlighted in bold.

	AUC		Cit_{max}		T_{max}		$T_{½max}$	
	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value
Tomato soup								
Burn	**33.0**	**<0.001**	**40.3**	**<0.001**	**12.4**	**<0.001**	–	–
Saltiness	2.2	0.11	0.5	0.63	2.0	0.14	1.1	0.34
Sweetness	**3.6**	**0.03**	**4.7**	**0.01**	0.3	0.76	**2.8**	**0.03**
Sourness	**9.9**	**0.01**	1.0	0.40	0.5	0.75	**2.2**	**0.04**
Tomato flavor	**23.5**	**<0.001**	**3.6**	**0.03**	0.2	0.96	**12.4**	**<0.001**
Creaminess	**14.4**	**<0.001**	0.9	0.07	0.3	0.89	**9.8**	**<0.001**
Thickness	0.5	0.75	0.3	0.85	0.3	0.85	0.3	0.89
Curried rice								
Burn	**40.2**	**<0.001**	**36.6**	**<0.001**	**18.6**	**0.01**	–	–
Saltiness	2.1	0.07	2.0	0.14	**4.3**	**0.03**	0.3	0.75
Sweetness	**20.2**	**<0.001**	**2.1**	**0.04**	2.0	0.20	**18.2**	**<0.001**
Rice flavor	**6.8**	**0.02**	**3.9**	**0.03**	1.6	0.14	**19.8**	**<0.001**
Coconut flavor	**15.8**	**<0.001**	**6.2**	**0.01**	0.3	0.89	**21.2**	**<0.001**
Creaminess	**7.0**	**0.01**	**3.3**	**0.03**	**17.6**	**0.01**	0.3	0.76
Hardness	0.3	0.89	0.3	0.80	1.1	0.34	**10.3**	**<0.001**
Chewiness	0.8	0.43	0.6	0.62	3.6	0.08	2.0	0.14
Graininess	0.8	0.54	0.3	0.90	0.8	0.54	2.2	0.11
Beef patty								
Burn	**36.7**	**<0.001**	**30.6**	**<0.001**	**28.9**	**<0.001**	–	–
Saltiness	0.3	0.89	0.3	0.85	1.6	0.15	0.3	0.75
Beef flavor	**15.8**	**<0.001**	**2.9**	**0.04**	**4.3**	**0.03**	**17.3**	**<0.001**
Garlic flavor	**21.5**	**<0.001**	**3.5**	**0.03**	2.2	0.07	0.2	0.90
Hardness	0.5	0.75	2.3	0.12	0.5	0.75	**2.0**	**0.04**
Chewiness	0.3	0.90	0.3	0.80	1.2	0.34	1.1	0.34
Graininess	0.5	0.75	0.9	0.41	1.1	0.34	0.3	0.89
Juiciness	0.1	0.79	1.1	0.34	2.1	0.08	0.7	0.62
Fattiness	0.8	0.54	**2.2**	**0.04**	**22.2**	**<0.001**	**2.6**	**0.04**

(Table 4 and 5). Similar to AUC, Cit_{max} decreased for sweetness, rice flavor, coconut flavor and creaminess. Relative to control curried rice, Cit_{max} of CAP-Low/High and CHI-Low/High curried rice significantly ($p < 0.05$) decreased by up to 26 % for sweetness, by up to 20 % for rice flavor, by up to 41 % for coconut flavor and by up to 44 % for creaminess. T_{max} of saltiness significantly decreased for all curried rice with CAP or CHI compared to control while T_{max} of creaminess significantly increased by up to 6 s for CHI-High curried rice compared to control. With the addition of capsaicin or ground dried chili, the maximum decrease in $T_{½max}$ that was observed in CAP-Low/High and CHI-Low/High curried rice: $T_{½max}$ significantly decreased ($p < 0.001$) by up to 43 % for sweetness, by up to 47 % for coconut flavor, by up to 21 % for rice flavor and by up to 32 % for hardness respectively compared to control curried rice (Table 4 and 5). This confirmed that oral burn provoked by capsaicin and chili suppressed dynamic perception of coconut flavor, rice flavor, sweetness and creaminess and shortened the lingering of coconut flavor, rice flavor, sweetness and hardness in curried rice.

3.4. Impact of capsaicin and chili pepper on dynamic sensory perception of beef patties

3.4.1. Effect of chili/capsaicin addition on burn of beef patties

Fig. 2c and Fig. 5 show the TCATA curves for beef patties, Table 4 and 5 summarize and compare the parameters extracted from the TCATA curves for beef patties. Control beef patty (Fig. 2c) had the lowest citation proportion for the burn with a Cit_{max} of 0.147. Significant differences in the citation proportions of burn were found with the addition of capsaicin (Fig. 5b-5c), and chili (Fig. 5d-5e) to beef patties throughout the entire evaluation process, suggesting that the addition of capsaicin and chili resulted in a dynamic and long-lasting burn (Fig. 2c, bold lines). At the beginning of the evaluation (<10 s), TCATA profiles of burn for CAP-Low/High beef patties were similar to those of CHI-Low/High beef patties (Fig. 3c). Later in the evaluation (>10 s), TCATA profiles of burn displayed differences between CAP-Low/High and CHI-Low/High beef patties. The citation proportion of burn surpassed that of other sensory attributes after swallowing moment at around 55 s for CAP-Low beef patty (Fig. 5b) and around 44 s for CAP-High beef patty (Fig. 5c), whereas the citation proportion of burn exceeded that of other sensory attributes before swallowing at around 30 s for CHI-Low beef patty (Fig. 5d) and at around 23 s for CHI-High beef patty (Fig. 5e).

Relative to control, the maximum citation proportion of burn significantly ($p < 0.001$) increased by 0.386 peaking at 62 s for CAP-Low beef patty and by 0.480 peaking at 52 s for CAP-High beef patty (Table 4 and 5). Similarly, Cit_{max} of burn significantly ($p < 0.001$) increased by 0.566 peaking at 58 s for the CHI-Low beef patty, and by 0.700 peaking at 60 s for the CHI-High beef patty (Table 4 and 5). Areas under the curve (AUCs) of burn differed significantly ($p < 0.001$) among beef patties and displayed the largest AUC value for CHI-High beef patty, which were significantly higher than those of other beef patties suggesting that high concentration of ground dried chili led to a strong and long-lasting burn. The addition of ground dried chili to beef patty led to a larger AUC of burn compared to the addition of capsaicin. Maximum burn perception of CAP-High was reached significantly earlier than for CHI-High in curried rice (Table 4) indicating that the build up of oral burn in beef patty was faster for capsaicin than for ground dried chili when burn intensity was high.

3.4.2. Effect of burn on taste, flavor and mouthfeel perception of beef patties

The TCATA profile of the control beef patty (Fig. 5a) was characterized by the perception of beef flavor, especially before swallowing, reaching its highest citation proportion (0.747) at 9 s, followed by chewiness (0.527), garlic flavor (0.500) and saltiness (0.480) reaching their highest citation proportions at 37 s, 26 s and 17 s, respectively. The end of the evaluation of the control beef patty was characterized by high

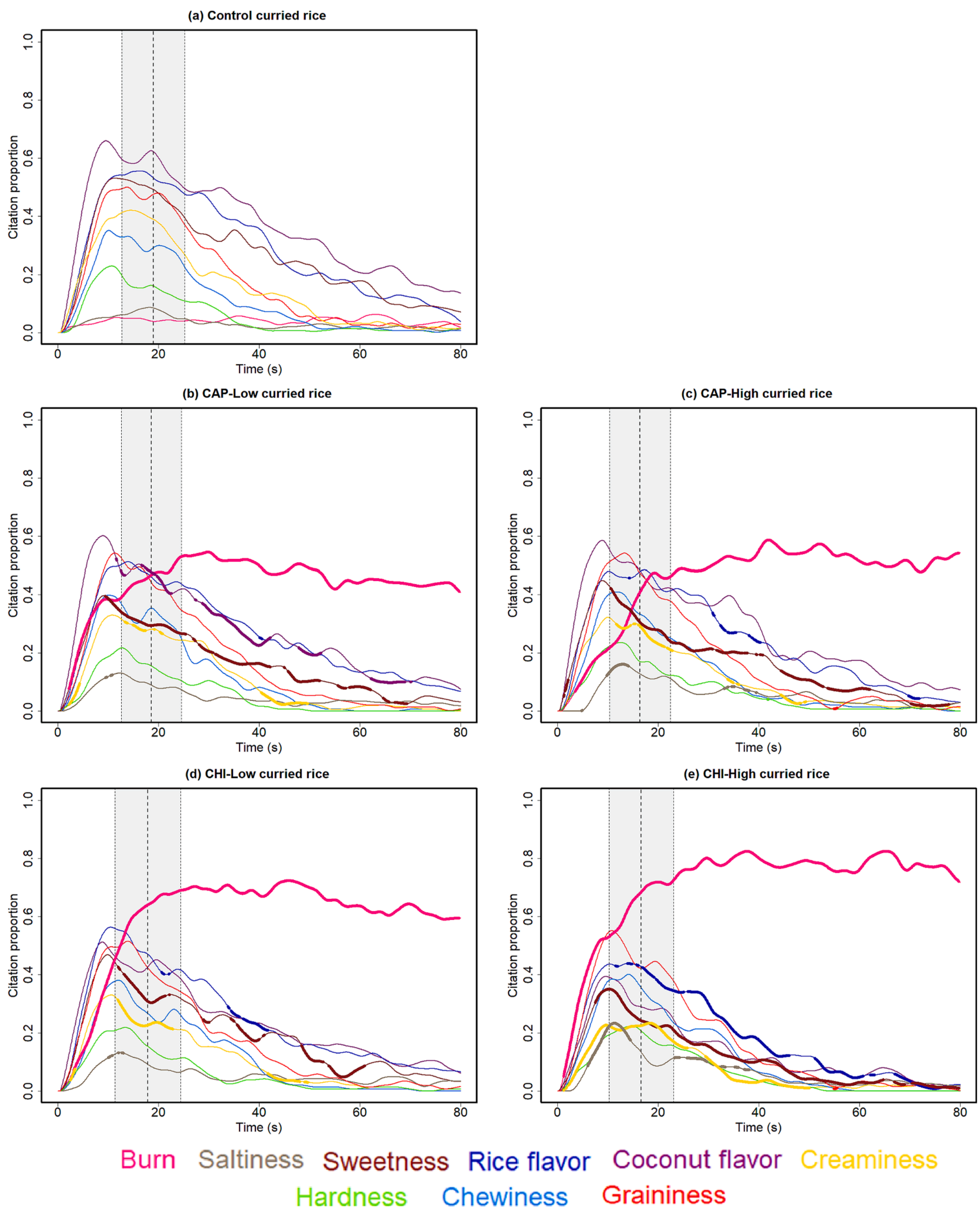

Fig. 4. TCATA curves (n = 73, duplicate) of (a) curried rice without capsaicin/chili (control) and (b-c) curried rice with added capsaicin (CAP) at low (b) and high (c) concentrations and (d-e) curried rice with added dried ground chili (CHI) at low (d) and high (e) concentration. Solid lines represent citation proportions for each sensory attribute. Highlighted bold sections indicate significant ($p < 0.05$) differences in citation proportions of an attribute during a time interval compared to the control curried rice. Vertical dotted lines represent the average swallowing moment and the grey area represents standard deviation. The legend indicates the color coding of the sensory attributes.

citation proportions of beef flavor and garlic flavor. Beef flavor, garlic flavor and fattiness of CAP-Low/High beef patties (Fig. 5b-5c) were less perceived after swallowing but with a short period (<10 s) during which they were significantly different from the control beef patty. Beef flavor, garlic flavor, fattiness, juiciness and saltiness of CHI-low/High were perceived less but with a longer (>15 s) period of significant difference from swallowing through the end of the evaluation. Overall, beef flavor and garlic flavor showed a decrease in perception with long significantly different periods of the evaluation. After swallowing, the perception of burn had the highest citation proportion, followed by high citation proportions of beef flavor until the end of the evaluation.

Relative to control beef patty, AUC values of CAP-Low/High and CHI-Low/High beef patties significantly ($p < 0.001$) decreased by up to 25 % for beef flavor and by up to 37 % for garlic flavor, respectively (Table 4 and 5). Similarly, Cit_{max} of CAP-Low/High and CHI-Low/High beef patties significantly ($p < 0.05$) decreased by up to 13 % for beef flavor, by up to 29 % for garlic flavor and by up to 35 % for fattiness respectively relative to control beef patty (Table 4 and 5). Compared with the control beef patty, T_{max} of beef flavor significantly increased from 9 s (control) to 17 s for CHI-High beef patty, and T_{max} of fattiness significantly decreased from 32 s (control) to 15 s for Chi-High beef patty. With the addition of capsaicin or ground dried chili, the maximum decrease in $T_{½max}$ that was observed in the four samples: $T_{½max}$ significantly decreased by up to 15 % for beef flavor, by up to 28 % for

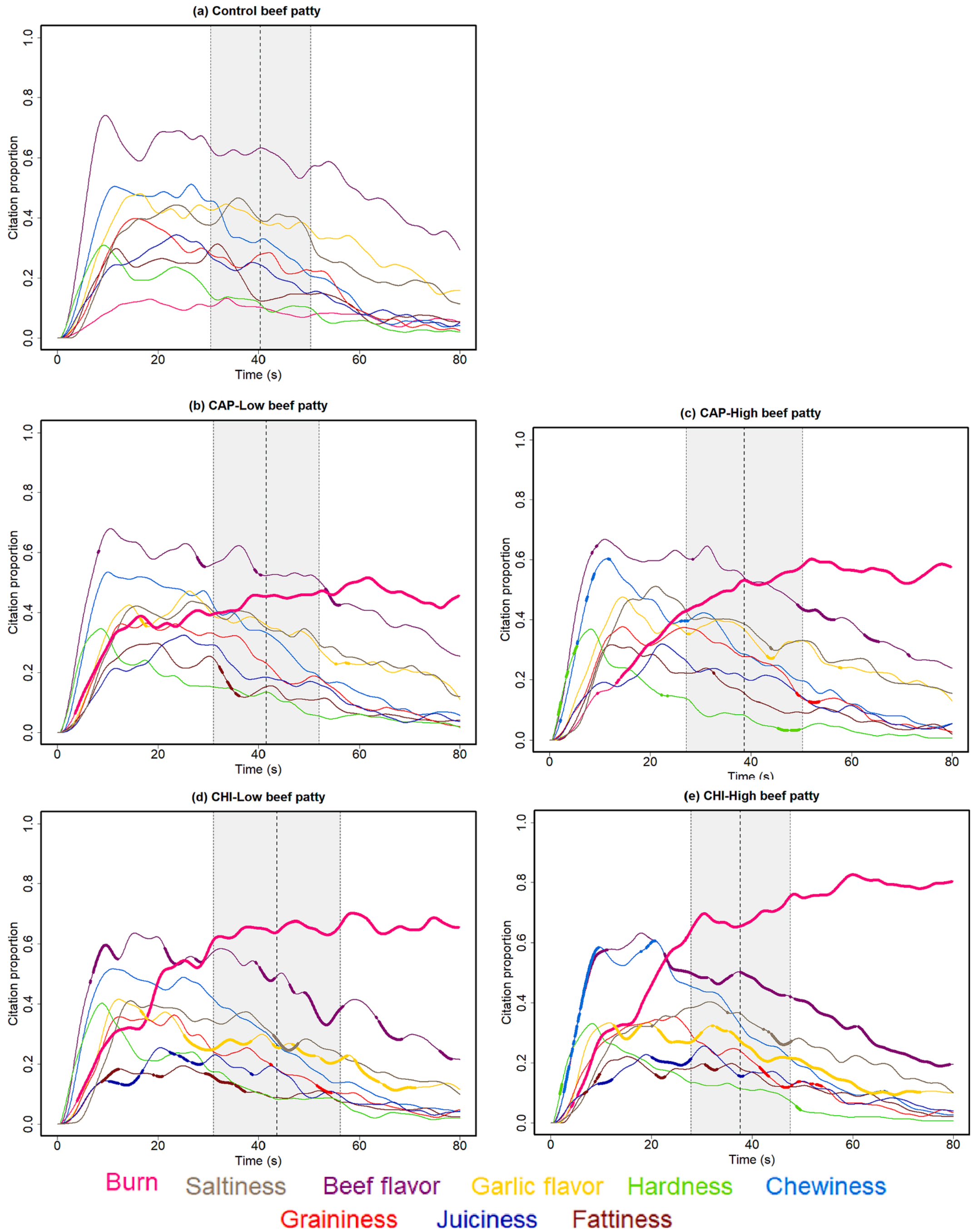

Fig. 5. TCATA curves (n = 73, duplicate) of (a) beef patty without capsaicin/chili (control) and (b-c) beef patty with added capsaicin (CAP) at low (b) and high (c) concentration and (d-e) beef patty with added dried ground chili (CHI) at low (d) and high (e) concentration. The solid lines represent citation proportions for each sensory attribute. Highlighted bold sections indicate significant ($p < 0.05$) differences in citation proportions of an attribute during a time interval compared to the control beef patty. Vertical dotted lines represent the average swallowing moment and the grey area represents standard deviation. The legend indicates the color coding of the sensory attributes.

hardness, by up to 14 % for fattiness respectively compared to control beef patty (Table 4 and 5). This confirmed that oral burn provoked by capsaicin and chili suppressed perception of beef flavor, garlic flavor and fattiness in beef patties and shortened the lingering of beef flavor, hardness and fattiness.

4. Discussion

This study aimed to determine the effect of oral burn on temporal taste, flavor and mouthfeel perception in liquid (tomato soup) and solid (curried rice and beef patties) foods. In addition, we compared the temporal oral burn of capsaicin to ground dried chili powder at different concentrations to quantify their relative impact of oral burn on temporal taste, flavor and mouthfeel perception of three common foods.

We hypothesized that capsaicin and ground dried chili would display distinct temporal burn intensity profiles and that the oral burn of ground dried chili would be perceived faster than capsaicin. Indeed, capsaicin (CAP) solutions and ground dried chili (CHI) dispersions displayed different temporal profiles (Fig. 1a) with significant differences in I_{max} and AUC and no significant differences in T_{max} (Table 3). Temporal profiles of capsaicin solutions and ground dried chili were similar at low concentrations, with similar values of $T_{50\%max}$ (Table 3). However, at higher concentrations, $T_{50\%max}$ of capsaicin (CAP) solutions was significantly longer than $T_{50\%max}$ of ground dried chili (CHI) dispersions (Table 3), which was not in agreement with our first hypothesis. The rate of onset and temporal built-up of oral burn was independent of concentration and type of trigeminal stimulus, whereas the lingering of oral burn was strongly dependent on concentration (i.e. shorter lingering at low concentrations) and type of trigeminal stimulus (i.e. capsaicin burns longer than dried ground chili).

Burn intensity of capsaicin solutions and ground dried chili dispersions reached maximum intensity after similar periods between 15 and 20 s (Table 3). It is important to note that dose–response behavior was observed for both capsaicin solutions and ground dried chili dispersions showing a higher concentration led to higher burn intensity. The above results confirm that capsaicin and ground dried chili in an aqueous environment may evoke quite different temporal oral burn profiles. Capsaicin or chili concentrations used in this study were comparable with other studies (Carden et al., 1999; Cliff & Heymann, 1993; Green, 1989; Hutchinson et al., 1990; Lawless, 1984; Lawless & Stevens, 1988; Nasrawi & Pangborn, 1990a). One possible explanation might be that trigeminal compound release differed between capsaicin and ground dried chilies due to the solubility difference between capsaicin and chili in an aqueous environment. Capsaicin was dissolved in the aqueous solution which might have caused longer binding to the trigeminal receptors, while trigeminal active compounds in ground dried chili dispersions did not fully dissolve in water hence it might have been cleansed from the palate and the receptors faster.

Food matrices played an important role in the observed differences in burn perception, where the overall temporality of burn depended on the food matrix but was independent of concentration and type of trigeminal stimulus. TCATA curves (Fig. 2) differed in maximum citation proportions, but the overall trajectory was similar for CAP-Low/High and CHI-Low/High foods. The citation proportion of burn reached the highest citation proportion at 19–30 s for the liquid food matrix (tomato soup). For curried rice, the citation proportions reached peaked at 30–45 s while for beef patties the peak was reached at 52–62 s. This effect might be explained by differences in the oral exposure time of each of the three foods, as the solid food with the longest oro-sensory exposure took the longest to reach peak citations for an equivalent concentration. Liquids (Tomato soup) displayed the shortest oral exposure time (around 6 s on average), whereas curried rice had an average oral exposure time of 18 s while beef patties had the longest (40 s on average). We speculate that shorter oral exposure time of liquids allowed burn to peak early and led to a more rapid decline in burn towards the end of the evaluation. The liquid nature of the tomato soup also encouraged greater interaction with the taste receptor and provided easy access to the trigeminal nerve endings for both the capsaicin and dissolved ground chili powder. The solid foods were swallowed later and required greater mastication and breakdown of the solid food matrix for the trigeminal stimulus (chili/capsaicin) to be solubilized in the saliva before it could interact with the trigeminal nerve endings on the tongue. As such, burn peaked later but was retained for longer with a slower decline during the evaluation period. Solid foods needed to be chewed and masticated to fragment food particles (masticated for 16–19 s and 37–44 s, respectively), so that they are well mixed and properly lubricated by the saliva to form a coherent bolus that can be swallowed safely and comfortably (Alexander, 1998; Chen, 2009, 2015; Hoebler, 2000). Furthermore, chewing and mastication increases saliva production and food structure breakdown which enhances flavor and aroma release. This could explain why the citation proportion of burn always peaked after swallowing across the three food products. Differences between the two solid foods may be due to food structure and matrix, but could also be influenced by composition, as the burger patty contained significantly more fat than the rice, which may have acted as a non-polar reservoir for the hydrophobic capsaicin. As such, this may have delayed the release and solubilization of the capsaicin and chili powder in saliva, and subsequent burn perception. The type and concentration of chemical irritants also impacted the temporal onset of burn sensation. Citation proportions of burn from capsaicin surpassed those of other sensory attributes before swallowing, while the citation proportions of burn of foods with added chili surpassed those of other sensory attributes after swallowing. This suggests that the dynamics of burn perception were influenced by food matrix, structure and its onset was related to the type and concentration of the chemical irritant, as it relates to the other sensory attributes.

We hypothesized that adding capsaicin and ground dried chili to tomato soup, curried rice and beef patty would lead to a suppression of taste, flavor and mouthfeel perception. Results consistently show that across all three food matrices increasing oral burn caused by addition of capsaicin or ground dried chili led to a prolonged suppression of taste, flavor and mouthfeel perception, as seen in the reduced AUC and Cit_{max}. These results are in line with previous findings and provide further evidence for a general suppressive effect of oral burn on taste, flavor and mouthfeel across different sensory modalities and across different foods. These results are in agreement with our previous study which employed static RATA (Rate-All-That-Apply) and showed that oral burn produced by chili significantly suppressed the perception of beef flavor intensity in beef patties, as well as the intensity of tomato flavor, sweetness and sourness in tomato soup (Lyu et al., 2022). Kostyra et al. (2010) evaluated the interactions between burn and taste or flavor perception in tomato, chicken, and mushroom soups and sauces, reporting that sauces resulted in lower burn intensities and that higher burn intensities suppressed flavor attributes. Reinbach et al. (2007) performed a comprehensive study on the interaction between oral burn and meat flavor in pork patties to which two chili products (chili powder and minced chili) were added. They showed that patties with chili powder were perceived hotter than those with minced chili, and that intensity of oral burn was oppositely related to the intensity of meat flavor while changes of the texture did not affect burn nor meat flavor intensity.

Adding capsaicin and ground dried chili to tomato soup, curried rice and beef patty significantly increased Cit_{max} of burn, and burn lingered for a long time (>80 s) so that $T_{½max}$ of burn could not be obtained as citation proportion of burn did not decrease to half of the maximum citation proportion (Fig. 2 and Table 4). $T_{½max}$ decreased significantly with oral burn for sweetness, sourness, tomato flavor and creaminess of tomato soups, for sweetness, rice flavor, coconut flavor and hardness of curried rice and beef flavor, hardness and fattiness of beef patties demonstrating that oral burn caused by two trigeminal stimuli shortened the lingering of taste, flavor and mouthfeel perceptions in three foods (Table 4 and 5).

Possible mechanisms have been proposed to explain the observed suppression effect of oral burn on taste, flavor and mouthfeel perception. Clark and Lawless (1994) suggested a potential attentional effect or "halo effect," that is, chemical irritant stimulation or burn draws attention away from the taste, smell, and mouthfeel perception when irritancy is sufficiently high. In other words, participants' ability to perceive tastants, odorants, and mouthfeel might have been reduced due to the dominant burn. Another explanation has been proposed by Lawless et al. (1985) who suggested that reduced taste or flavor intensity may result from the competition among sensory inputs in the central nervous system because the number of receptors and nerve fibers is limited, causing an increase in 'neural noise' in the sensory signal, and thus a possible neural inhibition. In this way, increased neural noise with increasing capsaicin concentration might cause a decline in taste, flavor and mouthfeel perception.

5. Conclusions

This study aimed to determine the effect of oral burn on temporal taste, flavor and mouthfeel perception across two trigeminal stimuli (capsaicin and chili powder) and three food matrices (tomato soup, curried rice and beef patties). We showed that burn build-up was not affected by concentration (Low vs. High) or type of trigeminal irritant (capsaicin vs. ground dried chili) in the aqueous environment. Burn intensity tended to linger for longer for the capsaicin solutions than for ground dried chili dispersions at high concentration, and was dependent on the oral burn intensity with higher oral burn causing longer-lasting burn. The addition of capsaicin and ground dried chili to all food matrices led to a significant increase in oral burn which suppressed taste and flavor across all foods. Both food structure (liquid vs. solid) and composition influenced the rate of onset and duration of the burn sensation which had a subsequent effect on the dynamics of suppression of taste and flavor attributes for each food product. We conclude that oral burn suppresses taste, flavor and mouthfeel perceptions and reduces the lingering of taste, flavor and mouthfeel perceptions in tomato soups, curried rice and beef patties while the temporal build up of taste, flavor and mouthfeel is influenced only to a limited extent. Further research is needed to elucidate the underlying mechanisms, and the potential impact of this perceptual suppression on meal enjoyment and intake.

CRediT authorship contribution statement

Cong Lyu: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Ciarán G. Forde:** Conceptualization, Resources, Supervision, Writing – original draft, Writing – review & editing. **Markus Stieger:** Conceptualization, Funding acquisition, Resources, Supervision, Writing – original draft, Writing – review & editing.

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

Data will be made available on request.

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