Temperature and relative humidity influence the ripening descriptors of Camembert-type cheeses throughout ripening

M.-N. Leclercq-Perlat,*†¹ M. Sicard,*† N. Perrot,*† I. C. Trelea,*† D. Picque,*† and G. Corrieu*†

*UMR GMPA, INRA 0782, 1 avenue Lucien Brétignières, 78850 Thiverval-Grignon, France.

†UMR GMPA, AgroParisTech, 1 avenue Lucien Brétignières, 78850 Thiverval-Grignon, France

ABSTRACT

Ripening descriptors are the main factors that determine consumers' preferences of soft cheeses. Six descriptors were defined to represent the sensory changes in Camembert cheeses: *Penicillium camemberti* appearance, cheese odor and rind color, creamy under-rind thickness and consistency, and core hardness. To evaluate the effects of the main process parameters on these descriptors, Camembert cheeses were ripened under different temperatures (8, 12, and 16°C) and relative humidity (RH; 88, 92, and 98%). The sensory descriptors were highly dependent on the temperature and RH used throughout ripening in a ripening chamber. All sensory descriptor changes could be explained by microorganism growth, pH, carbon substrate metabolism, and cheese moisture, as well as by microbial enzymatic activities. On d 40, at 8°C and 88% RH, all sensory descriptors scored the worst: the cheese was too dry, its odor and its color were similar to those of the unripe cheese, the under-rind was driest, and the core was hardest. At 16°C and 98% RH, the odor was strongly ammonia and the color was dark brown, and the creamy under-rind represented the entire thickness of the cheese but was completely runny, descriptors indicative of an over ripened cheese. Statistical analysis showed that the best ripening conditions to achieve an optimum balance between cheese sensory qualities and marketability were $13 \pm 1^\circ\text{C}$ and $94 \pm 1\%$ RH.

Key words: cheese ripening, ripening descriptors, temperature, relative humidity

INTRODUCTION

Among the environmental parameters that affect the ripening of Camembert-type cheese, temperature, relative humidity (RH), and the composition of the gaseous atmosphere in the ripening chamber have the most effect on sensory properties (von Weissenfluh and Puhani,

1987; Choisy et al., 2000; Ramet, 2000). These previous studies highlighted the predominant role of temperature and reported that small increases in temperature can accelerate cheese ripening but can also produce off-flavor components or inconsumable products. This is in agreement with similar studies on Cheddar (Hannon et al., 2005) and Reggiano Argentinian cheeses (Sihufe et al., 2010). Bonaïti et al. (2004) showed that temperature and RH influence creamy under-rind thickness and the consistency of a smear cheese: at 16°C under 100% RH, the under-rind became completely runny after 20 d of ripening. It is recognized that the sensory properties of soft cheeses, such as surface-coating appearance, rind color, and cheese odor, are essential because they determine the choice and preferences of consumers (Dufossé et al., 2005).

To our knowledge, no research on the ripening conditions of Camembert-type cheeses has yet focused on the influence of ripening temperature and RH on ripening properties. Knowledge is lacking on the links between microbiological and physicochemical phenomena and the changes in cheese sensory properties. According to Perrot et al. (2004) and Sicard et al. (2011), cheese-makers often play an important role in this field. In factories, they may use instrumental measurements and empirical sensory perceptions at the same time (Perrot et al., 2004; Picque et al., 2006), and they may interact with automatic systems to assess the sensory properties of the cheeses and to monitor the ripening process. According to Lemoine (2001), the cheese-maker's assessment and reasoning still play a major role in the cheese ripening process, especially concerning sensory property control. Recently, Sicard et al. (2011) showed that it is possible to study the Camembert ripening process by macroscopic evolutions of cheeses evaluated from an expert's point of view. Those authors established a correlation of 76% between the microbiological, physicochemical, and biochemical data and the sensory phases measured according to expert knowledge.

The aim of this study was to evaluate the effects of ripening temperature (θ) and RH on the development of sensory properties in Camembert-type cheeses throughout their ripening (from d 0 to 40) for the same

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¹Corresponding author: perlat@grignon.inra.fr

set of cheese-making runs. The sensory ripening descriptors were studied in association with the microbial and physicochemical evolutions that occur during ripening.

MATERIALS AND METHODS

Camembert Cheese-Making and Ripening

The microorganisms used (*Kluyveromyces marxianus*, *Geotrichum candidum*, *Penicillium camemberti*, and *Brevibacterium aurantiacum*) and the cheese-making process were described previously (Leclercq-Perlat et al., 2012). Surface-mold-ripened soft cheeses (100 cheeses per cheese-making run, each weighing 300 ± 20 g) were manufactured in a sterile environment. The cheeses were aseptically transferred to a previously sterilized ripening chamber. After 24 h at 12°C and 85 ± 1% RH, they were maintained at 8, 12, or 16°C and 88, 92, or 98% RH, with a periodically renewed atmosphere. To do this, the ripening chamber was sealed on d 0. The concentration of CO₂ increased during ripening and was automatically decreased to 0.1% when it reached 0.5% by injecting humid sterile air (Picque et al., 2006). The cheeses were turned on d 5. On d 13, they were maintained at 12°C and 85% RH for 24 h. On d 14, the cheeses were then wrapped in a reference wrap (CdL, Amcor Flexibles, Barbézieux, France) and ripened at 4°C until d 40. This wrap was described by Picque et al. (2010).

Sensory Analysis Performed on the Cheeses

Sensory analyses were performed on each cheese sample under the same light and temperature (14 ± 1°C) conditions. Sensory evaluation was performed by 5 assessors according to the methodology used by Sicard et al. (2011). Each expert assessed each cheese, taking 5 descriptors generally used by cheese-makers into account, and scored descriptors on a scale from 1 to 5 (Table 1). Six sessions were devoted to training and evaluation before validating the panel’s performance (Sicard et al., 2011). To determine the progress of Camembert-type cheese ripening, the appearance of the cheese (*P.*

camemberti coating density and surface covering) was assessed as previously described by Bonaiti et al. (2004) and Sicard et al. (2011). The appearance of *P. camemberti* was assessed in terms of mycelium density and uniformity, varying from 1 (less than 10% of the cheese surface covered by *P. camemberti* mycelium) to 5 (more than 90% of the surface covered by *P. camemberti*). In addition, for each cheese sample, cheese odor, rind color under the *P. camemberti* coating, underrind consistency (**C_{UR}**), and core hardness (**H_{core}**) on d 14 and 40 were considered. The greatest difference between 2 panelists for each sensory descriptor was <0.2. The overall cheese odor varied from fresh cheese (score 1) to ammonia (score 5); the typical odor of Camembert corresponded to a score of 3. Cheese color under the *P. camemberti* coating varied from white (score 1) to dark brown (score 5); the typical color (cream) of a Camembert corresponded to a score of 3. Creamy underrind thickness is a key factor that characterizes progress of Camembert ripening (Leclercq-Perlat et al., 2004a, 2006, 2012), but its assessment requires destruction of the cheese. Consequently, cheese-makers use another descriptor, **C_{UR}**, that characterizes the texture of the ripened part of the cheese, as highlighted by Sicard et al. (2011). The creamy underrind thickness (**T_{UR}**, mm) was measured using a decimeter with an accuracy of 0.2 mm. The underrind consistency (Picque et al., 2010) varied from dry (score 1) to very runny (score 5). The **H_{core}**, characterizing the texture of the core part, was estimated by the ease with which the cheese was ground with a mortar and pestle. This hardness varied from very soft (score 1) to very hard (score 5). To simplify the analysis, only 2 characteristic days of ripening were considered: wrapping day (d 14) and the end of ripening (d 40), corresponding to the end of shelf-life for the cheeses.

Experimental Design

The effects of θ and RH on cheese sensory descriptors were examined using a 2-factor, 3-level complete factorial experimental design (3²) as described by Leclercq-

Table 1. Definition and score of the descriptors used to evaluate the Camembert-type cheese ripening process

Descriptor	Notation	Scale and reference				
		1	2	3	4	5
PC coverage ¹	N _{PC}	<10%	25%	50%	75%	>90%
Overall odor	Odor	Fresh cheese	Musty	Camembert	Camembert ammonia	Ammonia
Rind color	Color	White	Cream	Dark cream	Light brown	Dark brown
Underrind consistency	C _{UR}	Very dry	Dry	Soft	Soft with runny edge	Runny
Core hardness	H _{core}	Very soft	Soft	Medium	Hard	Very hard

¹PC = *Penicillium camemberti*.

Table 2. Descriptors of *Penicillium camemberti* appearance¹ obtained for each temperature (θ , °C) and relative humidity (RH, %) used during Camembert-type cheese ripening

Run	θ (°C)	RH (%)	t_{PCm}	N_{PC14}	N_{PC40}
1	8	88	10	2	2
2	8	92	10	2	3
3	8	98	9	3	2
4	8	98	9	3	2
3 and 4	8	98	9	3	2
5	12	88	6	4	5
6	12	92	4.5	5	5
7	12	92	5	5	5
8	12	92	5	5	5
9	12	92	4.5	5	5
10	12	92	5	5	5
6 to 10	12	92	5	5	5
11	12	98	4	4	3
12	16	88	3	4	2
13	16	88	3	4	2
12 and 13	16	88	3	4	2
14	16	92	3	3	3
15	16	98	3	2	1

¹ t_{PCm} = day on which *P. camemberti* mycelium is visually detected by the panel (SD = 0.5 d); N_{PC14} and N_{PC40} = the appearance notation on d 14 (before wrapping) and on d 40 (end of ripening), respectively. Values in bold are the average of each descriptor for runs carried out under the same conditions of ripening.

Perlat et al. (2012). The 9 combinations of θ and RH are shown in Tables 2 and 3. The levels of each factor used were 8, 12, and 16°C for θ and 88, 92, and 98% for RH. These levels were chosen according to the range of θ and RH generally used for Camembert cheese ripening. Because the experiments took place over a long period, the runs corresponding to the central point of the experimental design (12°C, 92% RH) were quintupled (runs 6 to 10). The runs under 8°C and 98% RH (runs 3 and 4) and those under 16°C and 88% RH (runs 12 and 13) were duplicated. The remaining runs were done just once.

Statistical Analyses

For the runs made under the same conditions (runs 3 and 4; runs 6 to 10, and runs 12 and 13), sensory descriptors were compared by a 2-factor (time and trial) ANOVA. The hypotheses examined were the equality of the trials and the absence of any interactions. This test was significant for the risk α [$\alpha = 1 - P(F_{obs} < F_{crit})] \leq 0.01$, where P is the P -value, F_{obs} is the Fisher coefficient obtained with the observed values, and F_{crit} is that obtained from the Student table of the degrees of freedom of the relationship. To control the equality of trials, the test power ($1 - \beta$), representing the risk of a false interpretation, was determined according to Mann and Whitney's method (Cohen, 1992). This power risk must be >0.9 for the interpretation of this test to be considered accurate. The general linear model within Statistica software (StatSoft, Paris, France) was performed to calculate quadratic models and to determine

the influence of the 2 factors (θ , RH) on each sensory descriptor. The nonsignificant terms were omitted one by one using the stepwise backward procedure (Statistica). Consequently, only terms significant at 99% of the confidence level ($P < 0.01$) were considered. The 3-dimensional response surfaces of each descriptor in relation to θ and RH were plotted to illustrate the main and interactive effects. These effects can be linear, quadratic, or interactive.

RESULTS AND DISCUSSION

For all runs, *P. camemberti* appearance (absence of visible mycelia), overall odor (fresh cheese), and rind color (white) scored 1 on d 0, and H_{core} scored 3 (medium). For these descriptors, the standard deviations were less than 0.2. The underrind did not exist on d 0.

Description of Cheese Ripening at 12°C and 92% RH: Reproducibility

The reproducibility of cheese ripening descriptors was studied for runs 6 to 10 carried out under 12°C and 92% RH (Table 2). The hypotheses of equality of the means were highly satisfactory [$1 - \alpha = 0.99$ and the test power ($1 - \beta$) = 0.94].

The time at which the first mycelia were observed in the rind or along the edge of the cheeses (t_{PCm} ; d) defined the growth of *P. camemberti* mycelia, and the appearance of the *P. camemberti* (N_{PC}) covering was defined in terms of mycelium density and uniformity of mycelium distribution on the surface. Regardless of

Table 3. Scores of ripening descriptors¹ of Camembert-type cheese ripening on d 14 (before wrapping) and on d 40 (end of ripening) obtained for each temperature (θ , °C) and relative humidity (RH, %)

Run	θ (°C)	RH (%)	On d 14 (before wrapping)					On d 40 (at the end of ripening)				
			Odor	Color	T _{UR}	C _{UR}	H _{core}	Odor	Color	T _{UR}	C _{UR}	H _{core}
1	8	88	2	1	1.3	1	4	2	1	9.5	1	4
2	8	92	2	1	1.8	1	4	2	1	10.5	2	4
3	8	98	2	1.5	2.0	2	3	3	2	10	3	4
4	8	98	2	1.5	2.0	2	3	3	2	10	3	4
3 and 4	8	98	2	1.5	2.0	2	3	3	2	10	3	4
5	12	88	3	1	2.7	2	5	4	2	11	2	5
6	12	92	3.5	2	3.3	3	3	4	3	14	3	1
7	12	92	3.5	2	3.3	3	3	4	3	14	3	1
8	12	92	3.5	2	3.5	3	3	4	3	14	3	1
9	12	92	3.5	2	3.4	3	3	4	3	14	3	1
10	12	92	3.5	2	3.3	3	3	4	3	14	3	1
6 to 10	12	92	3.5	2	3.3	3	3	4	3	14	3	1
11	12	98	3.5	2	4.1	3	2	4.5	3	14	4	1
12	16	88	4	3	3.9	4	5	4	4	12.5	4	3
13	16	88	4	3	3.9	4	5	4	4	12	4	3
12 and 13	16	88	4	3	3.9	4	5	4	4	12	4	3
14	16	92	5	4	5.7	5	4	5	5	14	5	— ²
15	16	98	5	4	6.0	5	3	5	5	14	5	—

¹Overall rind cheese odor varied from fresh cheese (score of 1) to ammonia (score of 5); cheese color under the *P. camemberti* coating varied from white (score of 1) to dark brown (score of 5); T_{UR} = underrind thickness (mm; SD = 0.5 mm); C_{UR} = underrind consistency, which varied from a dry (score of 1) to a very runny underrind (score 5); H_{core} = cheese core hardness, estimated by the ease with which the cheese could be ground with a mortar and pestle from very soft (score 1) to very hard (score 5). Values in bold are the average of each descriptor for runs carried out under the same conditions of ripening.

²Core was totally ripened and liquid and assessors could not evaluate the hardness.

the central point runs (6 to 10), *P. camemberti* mycelia became visible on d 5. From d 14 to 40, all cheeses were covered with a thick dense and white mycelium, giving the maximum score (Table 2).

On d 14, the overall odor and rind color were “camembert” and “cream,” respectively, whereas on d 40, they were “camembert-ammonia” and “dark cream,” respectively (Table 3).

On d 14 and 40, H_{core} was medium and C_{UR} was soft. The value of T_{UR} was close to 3.3 mm on d 14 and took up the entire cheese thickness on d 40 (Table 3). For the 5 runs carried out under standard ripening conditions (runs 6 to 10), all descriptors were statistically identical with 99% confidence levels.

Influence of Temperature and RH on Cheese Ripening Descriptors

The scores of ripening descriptors are reported in Table 2 for *P. camemberti* appearance and in Table 3 for the other descriptors. Table 4 reports the main significant relationships established between the descriptors and θ and RH. Figures 1 and 2 correspond to 3-dimensional response surface plots of the descriptors as a function of θ and RH.

Appearance of *Penicillium camemberti*

The time at which mycelium appeared (t_{PCm}) was independent of RH and only related to θ (Table 2).

As shown in Table 4, the appearance of *P. camemberti* mycelium on d 14 (N_{PC14}) was a function of θ (linear and quadratic terms), RH (linear term), and θ and RH (interactive term); on d 40 (N_{PC40}), it was related to θ and RH (linear and quadratic terms). The N_{PC14} surface response (Figure 1A) showed a main effect of θ . In fact, N_{PC14} increased with θ from 8°C to approximately 12°C and decreased thereafter (quadratic effect). The RH effect was relatively smaller and depended on θ , revealing an interactive effect: N_{PC14} increased with RH at low θ and decreased with RH at high θ . The N_{PC40} surface response (Figure 1B) showed the importance of the quadratic effects of θ and RH: N_{PC40} reached its maximum value for a θ of approximately 12°C and a RH of approximately 93%.

Ripening in the chamber at 16°C under 98% RH promoted *P. camemberti* sporulation, as previously shown by Leclercq-Perlat et al. (2012). Hardy et al. (2000) and Lenoir et al. (1985) reported that optimal mycelium growth is obtained under 90 to 94% RH for a temperature between 10 and 14°C. Moreover, *P. camemberti* mycelium does not grow well at higher RH (Ramet, 2000). The white and down coating of the Camembert surface disappears when the RH of the ripening room exceeds 95% at 12 to 14°C, even if these conditions last only 2 or 3 d. However, neither the *P. camemberti* visual appearance nor the *P. camemberti* spore count gives an accurate idea of mycelium growth and development, the first due to limitations of the human eye (saturation

Table 4. Best-fit equations for the effects of temperature and relative humidity on Camembert-type cheese ripening descriptors; all factors of the equations for temperature (θ , °C) and relative humidity (RH, %) are given (SD of the coefficient in parentheses)

Descriptor ₁	Equation					
	Y-intercept	θ	RH	θ^2	RH ²	$\theta \times \text{RH}$
On wrapping day (d 14)						
N _{PC14}	-54 (±10)**	+0.4 (±0.1)**	+0.4 (±0.1)*	-0.13 (±0.01)**		-0.039 (±0.008)**
Rind odor	-103 (±23)*	-0.8 (±0.2)*	+2.3 (±0.5)**	-0.013 (±0.003)**		+0.012 (±0.002)**
Rind color	-154 (±41)*	-0.7 (±0.02)*	+3.3 (±0.9)*	+0.042 (±0.007)**	-0.017 (±0.005)*	
T _{UR} (mm)	-1.8 (±0.3)**	-0.7 (±0.1)**				+0.012 (±0.001)**
C _{UR}	-11 (±2)**	+0.41 (±0.05)**	+0.10 (±0.02)**			
H _{core}	-10 (±1)*			+0.057 (±0.007)**		-0.014 (±0.002)**
At the end of ripening (d 40)						
N _{PC40}	-365 (±76)**	+3.1 (±0.3)**	+8.0 (±0.9)**	-0.13 (±0.01)**	-0.042 (±0.009)**	
Rind odor	-15 (±2)*	+1.0 (±0.2)**	+0.120 (±0.002)**	-0.030 (0.008)*		
Rind color	-11 (±1)**	+0.41 (±0.02)**	+0.10 (±0.02)**			
T _{UR} (mm)	-472 (±97)**		+10 (±2)**	-0.08 (±0.02)**	-0.06 (±0.01)**	+0.025 (±0.004)**
C _{UR}	-16 (±2)**	+0.33 (±0.02)**	+0.17 (±0.02)**			
H _{core}	NS					

N_{PCxx} = appearance notation of *Penicillium camemberti* at d 14 and 40; overall rind cheese odor varied from fresh cheese (score of 1) to ammonia (score of 5); cheese color under the *P. camemberti* coating varied from white (score of 1) to dark brown (score of 5); T_{UR} = underind thickness (mm); C_{UR} = underind consistency, which varied from a dry (score of 1) to a very runny underind (score 5); H_{core} = cheese core hardness, estimated by the ease with which the cheese could be ground with a mortar and pestle from very soft (score 1) to very hard (score 5).

* $P < 0.01$; ** $P < 0.001$.

when *P. camemberti* coating is complete) and the second because of the destruction of mycelium. Indeed, *P. camemberti* sporulation is accelerated throughout ripening by the temperature (Leclercq-Perlat et al., 2012, 2013). In the current study, the higher the temperature, the earlier growth of *P. camemberti* occurred and the earlier its concentration became maximal. Moreover, at 16°C and 98% RH, *P. camemberti* mycelium appeared damaged due to the disruption of the equilibrium between *P. camemberti* and *G. candidum* in favor of the yeast, whereas *P. camemberti* spore concentration was higher (Leclercq-Perlat et al., 2013).

Overall Cheese Odor

On d 14, cheese odor was described as “musty” at 8°C, “camembert” at 12°C, and “camembert-ammonia” at 16°C (Table 3). This descriptor was related to θ (individual and quadratic terms), RH (individual term), and θ and RH (interactive term; Table 4). In addition, odor uniformly increased at θ between 8 and 16°C, whereas the RH effect was almost negligible at 8°C and positive at 16°C (Figure 1C). On d 40, rind odor remained “musty” at 8°C under 88 and 92% RH, but became “camembert” under 98% RH. It was described as “camembert-ammonia” at 12°C regardless of RH and at 16°C and 88% RH. It was described as “ammonia” at 16°C under 92 and 98% RH. This descriptor was a function of θ (individual and quadratic terms) and RH (linear term; Table 4). The odor increased with θ , and RH had a constant positive linear effect, regardless of θ (Figure 1D).

An increase in θ induced better growth of the ripening microorganisms, mainly *G. candidum* and *P. camemberti* mycelium. When θ was >10°C, *B. aurantiacum* maximal exponential growth rate was reached on d 15 under 12°C and 92% RH, and just after wrapping, or on d 12 at 16°C and 88% RH (Leclercq-Perlat et al., 2012). A better expression of these enzymatic activities (promoting proteolysis and lipolysis) can also be induced by RH (Choisy et al., 2000). Moreover, an increase in temperature and RH can lead to an increase in the amount and variety of aroma compounds (Sablé and Cottureau, 1999; McSweeney and Sousa, 2000; Le Quéré, 2011).

By d 14, rind color increased with θ , from white, corresponding to a cheese with very little ripening (8°C under 88 and 92% RH or 12°C under 88% RH), to brown (16°C under 92 and 98% RH). By d 40, this color turned from white (8°C under 88 or 92% RH) to dark brown, an unacceptable color for a Camembert cheese (16°C under 92 or 98% RH).

Figure 1. Estimated response surface plots of some ripening descriptors as a function of temperature (θ , °C) and relative humidity (RH, %). *Penicillium camemberti* appearance notation (N_P ; score) on (A) d 14 and (B) d 40; odor (score) on (C) d 14 and (D) d 40; and color (score) on (E) d 14 and (F) d 40.

Figure 2. Estimated response surface plots of some ripening descriptors as a function of temperature (θ , °C) and relative humidity (RH, %). Underrind thickness (T_{UR} , mm) on (A) d 14 and (B) d 40; underrind consistency (C_{UR} ; score) on (C) d 14 and (D) d 40; and core hardness (score) on (E) d 14 and (F) d 40.

Rind Color

On d 14, rind color was a function of θ and RH (individual and quadratic terms), whereas on d 40, it was related only to θ and RH (individual terms; Table 4). Figure 1E shows the importance of quadratic terms on color on d 14, whereas Figure 1F shows that color increased uniformly with θ and RH (linear effects) on d 40. Rind color directly depends on the production of pigments by *Brevibacterium* species (Dufossé et al., 2001). At 8°C regardless of RH or at 12°C and 88% RH, a delay in yeast growth and *P. camemberti* mycelium development was observed (t_{PCm} in Table 2). Consequently, a delay in rind acidification and *B. aurantiacum* growth was observed (Leclercq-Perlat et al., 2012). The latter authors showed that, on d 40, at 8°C and 92 or 98% RH, *B. aurantiacum* counts were the lowest (between 6×10^6 and 2×10^8 cfu/g). In contrast, at 16°C under 92 or 98% RH, *B. aurantiacum* grew better, reaching 8×10^9 cfu/g, and rind deacidification took place earlier (d 2.5). At 16°C under 98% RH, *P. camemberti* mycelium disappeared after d 8, whereas mold sporulation increased (Leclercq-Perlat et al., 2013). These results highlight the dependence of rind color on RH due to better development of *B. aurantiacum* and a poor coating of *P. camemberti* mycelium when RH is >95%. Moreover, indirect positive interactions between yeasts, molds, and *B. aurantiacum* may increase proteolysis (Bockelmann et al., 1997) and can favor a better development of color (Leclercq-Perlat et al., 2004b; Lecocq et al., 1996).

Underrind Thickness

On d 14, T_{UR} increased by approximately 50% when θ increased from 8°C to 12°C, whereas it increased by between 32 and 40% when θ increased from 12°C to 16°C. On d 14, T_{UR} increased from 10% (8–12°C) to 15% (16°C) when the RH increased from 88 to 92%, whereas it increased from 9 to 17% when the RH increased from 92 to 98%. These results are in agreement with those of Gomes et al. (1998) and Gomes and Malcata (1998), who showed that temperature had a more important effect than RH for different proteolysis levels. In our study, T_{UR} on d 14 was related to θ (linear term) and θ and RH (interactive terms; Table 4) and it increased along the θ axis from 8 to 16°C; the temperature effect was stronger at higher RH values (Figure 2A). At 8°C on d 40, regardless of RH, T_{UR} reached around two-thirds of the cheese thickness (Table 3). This can be explained by a slowing of growth of all ripening microorganisms and by a limitation of their enzymatic activities due to the excessive drying of the

cheese or to temperature (Leclercq-Perlat et al., 2012). Lesage-Meessen and Cahagnier (1998) reported that microbial growth is repressed when the water activity, strongly linked to RH during ripening (Ramet, 2000), is progressively lowered. Regardless of θ , T_{UR} did not increase as much during ripening under 88% RH as under 92 or 98% RH. For other ripening conditions, the entire thickness of the cheese was ripened. This descriptor was related to θ (quadratic term) and RH (linear and quadratic terms) and their interactive term. These effects are shown in Figure 2B; T_{UR} exhibited a maximum at $14 \pm 1^\circ\text{C}$ and $93 \pm 1\%$ RH.

Underrind Consistency and Core Hardness

Regardless of θ under 88% RH, the score for C_{UR} was lower than that obtained at either 92 or 98% RH (Table 3). Under 8°C and 88% RH (run 1), the underrind was very dry on d 14 and 40. Only the central points (runs 6 to 10) had the soft and creamy underrind typical of a Camembert cheese (Table 3). For all RH at 16°C, cheeses did not have an acceptable underrind consistency because the underrind had runny edges (88% RH) or was completely runny (92 and 98% RH). The underrind consistency that showed almost linear increases along the θ and RH axes in the considered range (prevailing linear effects without interaction) confirmed the influences of θ (as the preponderant factor) and RH on d 14 (Figure 2C) and on d 40 (Figure 2D).

Under 88% RH on d 14, H_{core} was hard (at 8°C) or very hard (at 12°C or 16°C; Table 3). Regardless of θ under 92% or 98% RH, H_{core} remained medium under 88% RH on d 40. It remained hard at 8°C or very hard at 12°C but scored medium at 16°C. At 12°C or 16°C under 92 or 98% RH, the entire cheese thickness was ripened and H_{core} could not be scored by the assessors.

On d 14, H_{core} was a function of θ (individual term) and RH (interactive term; Figure 2E). This descriptor reached a minimum for θ that depended on the RH (interaction): it was approximately 13°C for 98% RH and approximately 11°C for 88% RH, as shown in Figure 2E. Core hardness decreased with increased RH, and the RH effect was slightly stronger for higher θ . On d 40, it was impossible to determine a relationship between H_{core} and ripening conditions because the entire cheese was ripened.

Both C_{UR} and H_{core} are descriptors of cheese texture. Cheese texture mainly depends on its pH, the entirety of caseins and lipids, and the moisture level (Lawrence et al., 1987). In fact, regardless of ripening conditions, the pH of the underrind is close to that of the rind (Leclercq-Perlat et al., 2012). This can be explained by the lactate and ammonium concentration gradients

that exist between the core and the rind (Vassal et al., 1986; Leclercq-Perlat et al., 2004a). Regardless of θ under 88% RH, the cheeses were not soft and did not have a creamy underrind due to (1) excessive drying of the cheese; (2) a delay in *K. marxianus* and *G. candidum* growth; (3) lower growth of *P. camemberti* and *B. aurantiacum* (Leclercq-Perlat et al., 2012, 2013); and (4) lower enzymatic activity as shown by overall cheese odor. In fact, at 16°C and 92% RH and at 12 or 16°C under 98% RH, the cheese underrind was completely runny, indicative of over-ripening. With the rapid increase of pH and its consequence on the texture, liquefaction of the underrind can be explained by breakdown of casein and associated enzymatic activities due to faster growth of microorganisms (Leclercq-Perlat et al., 2012, 2013).

The hydrolysis reactions that take place in cheese involve water fixation within the cheese core. Moreover, the breakdown products of caseins are largely water-soluble, and proteolytic activity in cheese is mainly determined by the level of moisture, the temperature of ripening, and changes in pH throughout ripening (Lawrence et al., 1987; Ramet, 2000).

In addition, changes in underrind consistency can be explained by the enzymatic activity of the surface-ripening flora, although the enzymes remain near their production site; that is, the cheese rind (Noomen, 1983). *Kluyveromyces marxianus* has only endocellular proteolytic activity (Klein et al., 2002), *G. candidum* strongly contributes to proteolysis by its extensive enzymatic system (Boutrou et Guéguen, 2005; Boutrou et al., 2006), *P. camemberti* has a complex proteolytic system that is more active when the pH of the rind is at least 6.0 (Lenoir et al., 1985; Choisy et al., 2000), and *B. aurantiacum* is well known for its considerable proteolytic activity (Lecocq et al., 1996; Rattray and Fox, 1999). Under 98% RH at 12°C and 92 or 98% RH at 16°C, Leclercq-Perlat et al. (2012) showed that (1) the death of *K. marxianus* begins earlier (d 25) and is more intensive than under the other ripening conditions; (2) *G. candidum* growth also began earlier (d 1 to 2), more rapidly reaching its maximal concentration; (3) *P. camemberti* spore concentrations were the highest, reaching approximately 5.5×10^6 spores/g on d 40 at 16°C; and (4) *B. aurantiacum* grew quickly as well, reaching a concentration of more than 1×10^9 cfu/g. Moreover, a synergy was observed between *G. candidum* and *P. camemberti*, the first allowing an easier assimilation of peptides and AA as carbon sources by *P. camemberti*, leading to a more intense proteolysis in the cheese underrind, confirming the studies of Aziza et al. (2005) and Aziza and Amrane (2006). Underrind consistency is also related to lipid breakdown mainly by

G. candidum and *P. camemberti* (Lenoir et al., 1985); *K. marxianus* and *B. aurantiacum* have no significant lipolytic activities (Leclercq-Perlat et al., 2007). Lipolytic enzyme activities mainly depend on temperature and cheese moisture, which is dependent on RH (Choisy et al., 2000; Ramet, 2000; Leclercq-Perlat et al., 2012). Subsequently, low RH leads to considerable dehydration of the cheese rind by water evaporation from the surface toward the atmosphere, and water diffuses from the cheese core toward the surface at the same time (Simal et al., 2001; Bonaïti et al., 2004). This dehydration increased with temperature: under 88% RH at 16°C, the cheese DM on d 14 and 40 was the greatest, 47% and $53 \pm 1\%$, respectively, leading to a slowing of ripening (Leclercq-Perlat et al., 2012). However, regardless of RH at 8°C, the core remained hard on d 40 although its DM (42–44%) did not differ from that of cheese under the other ripening conditions. This could be explained by a slowing of enzymatic reactions occurring in the cheese, probably due to the lower temperature. In contrast, under 98% RH at 12°C or 16°C, greater enzymatic activity and lower dehydration cause the cheese underrind to become liquid. Regardless of the temperature under 88% RH, the cheese water mass loss and the DM of the core were the highest (Leclercq-Perlat et al., 2012; study conducted at the same time as the current study and using the same cheeses). Consequently, cheese moisture is strongly influenced by the ripening conditions, confirming the importance of cheese moisture and, consequently, the importance of RH on core hardness.

CONCLUSIONS

The sensory properties of Camembert-type cheeses assessed by an expert panel were highly dependent on θ and RH used throughout ripening. All sensory descriptor changes (overall cheese odor and color, creamy underrind thickness and consistency, core hardness) can be explained by microorganism growth, pH increase, carbon substrate diffusion and assimilation and cheese moisture, as well as microbial enzymatic activity. All factors were also linked to θ and RH established in the ripening chamber at the beginning of the process (d 0 to 14). Under 88% RH at 8°C, all sensory descriptors scored the worst on d 40: the cheeses were too dry, their odor and color were similar to those of the cheeses defectively ripened, the underrind was the driest, and the core was hardest. In contrast, under 98% RH at 16°C, the odor and the color of the cheeses were ammonia and dark brown, respectively, and the creamy underrind represented the entire thickness of the cheeses but was completely runny. These descriptors were indicative

of over-ripened cheeses. The best ripening conditions to obtain an optimum between sensory qualities and cheese ripening properties appeared to be 13°C and 94% RH. Because all of the cheeses were wrapped with the same film and then ripened at 4°C, we established that the initial ripening conditions in the room (from d 0 to 14) determine the ripening of Camembert-type cheeses under wrapping. This type of study will provide the knowledge necessary (1) to develop a mechanistic model to monitor the Camembert-type cheese ripening process in relation to ripening conditions; (2) to slow down or accelerate the ripening process in relation to market demand; and (3) to correct some of the existing flaws in acceptable cheeses.

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