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# Visuo-tactile and topographic characterizations of finished wood surface quality by French consumers and industrials: acceptability thresholds for raised grain

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## Abstract

- **Key message** Raised grain occurring on wood surfaces after the application of a waterborne varnish was felt by human touch because of protruding peaks and a certain amount of materials in the core of the roughness profile. This tactile sensation was correlated with specific roughness parameters. Characteristics of a finished surface quality that is acceptable to consumers were determined.
- **Context** Raised grain occurs on wood surfaces after the application of a waterborne varnish and forces manufacturers to sand the surfaces between coats. Actually, little research has characterised this phenomenon and no techniques have been discovered to avoid its occurrence.
- **Aims** This study aims to identify the topographic parameters that explain the visuo-tactile sensation of raised grain and to define a finished surface quality acceptable to consumers and industry.
- **Methods** Oak (*Quercus robur* L.) and beech (*Fagus sylvatica* L.) wood surfaces were planed and sanded in order to have various levels of raised grain. Visuo-tactile analyses were carried out on surfaces having received one coat of varnish to characterise raised grain and having two coats to characterise the acceptable finished surface quality without sanding. Topographic parameters were measured on each type of varnished surface and correlated with the visuo-tactile scores.
- **Results** Raised grain was characterised by the visuo-tactile sensation of protruding peaks and a certain amount of material in the core of the roughness profile for both wood species. Industrials overestimated the surface quality required by consumers. Thresholds of topographic parameters were determined to define acceptable finished surface quality.
- **Conclusion** These findings allowed objective criteria to be defined for describing raised grain and to help industries to optimise their wood machining and finishing processes.

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**Contribution of the co-authors** Miora Ramanakoto and Florent Eyma carried out machining and finishing processes in industries, and carried out visuo-tactile analysis with industrials.

Miora Ramanakoto carried out visuo-tactile analysis with consumers, measured topographic parameters on wood surfaces, carried out statistical analysis and wrote the paper.

Miora Ramanakoto, Tahiana Ramananantoandro and Florent Eyma designed the study and the methodology, discussed the results, commented on the manuscript and wrote the paper.

Tahiana Ramananantoandro, Florent Eyma and Bruno Castanié supervised the work.

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**Keywords** Raised grain · Topographic parameters · Waterborne varnish · Visuo-tactile analysis · Planing · Sanding

## 1 Introduction

Finishing products can be applied to wood surfaces in one or more coats (NE EN ISO 2808 2007). The use of solvent-based finishes was restricted by the European Directive IED2010/75/EU of January 6, 2011, which calls for the reduction of volatile organic compound (VOC) emissions that are harmful to human health and the environment. Thus, since the 2000s, French firms using 80% organic solvents have had to turn to technologies that emit smaller amounts of VOC, and now use water-based products (Roux and Delorme 2012).

The main problem with a waterborne finishing product is that it produces noticeably raised grain on the wood surface and forces manufacturers to sand the surface between coats. This sanding operation, called “denibbing” by Ramananantoandro et al. (2017), is expensive (Taylor et al. 1999). Raised grain occurs from the swelling of wood fibres by the water, inducing the separation and lifting of individual fibres or groups or even fragments of fibres (Koehler 1932), and increases the surface roughness (Landry et al. 2013).

Several researchers have studied the factors responsible for raised grain on wood surfaces after machining and finishing. According to Marra and Syracuse (1932), the wood grain angle, i.e., the orientation of the wood grain with respect to the surface, is the most important variable in connection with the development of raised grain on oak woods, the maximum effect being observed to occur for angles between 3° and 15°. Singh et al. (2010) found that the occurrence of raised grain on the varnished surface of *Pinus radiata* was related to the wood moisture content. For Rajemison (2013), this phenomenon was more or less pronounced depending on the species, but the reasons for these differences were not investigated. The variations in physical, anatomical and chemical characteristics among species may help explain these behavioural differences. Evans et al. (2017) found that very low density woods were highly susceptible to raised grain, whereas it did not occur in high-density woods. Finally, the machining processes and the associated cutting conditions also have important effects on its occurrence. The majority of researchers have analysed this phenomenon on sanded surfaces and Ramananantoandro et al. (2017) found that, on beech, sanding favoured this phenomenon more than planing did. According to the same authors, the occurrence of raised grain on a planed surface was favoured by cutting conditions that produced a high average chip thickness. On sanded surfaces, Marra and Syracuse (1932) found that increasing the coarseness of the abrasive grit and sanding against the grain was conducive to raised grain.

Although previous studies have pointed out the factors responsible for raised grain and tried to objectively characterise this phenomenon, no method has yet been suggested to prevent its occurrence and to eliminate the denibbing operation. Moreover, no study has investigated the tactile preference of consumers in relation to raised grain. In the literature, studies that analysed the consumers’ preferences of wood products were focussed on the visual characteristics of the surface like grain orientation, colouration and knot characteristics (Manuel et al. 2015). Ramananantoandro et al. (2013) showed that the wood density was a prime criterion when consumers chose a wood species for furniture. Ramanakoto et al. (2017) investigated the visuo-tactile consumers’ preferences of machined wood surfaces without coatings and showed that consumers like smooth surfaces without visible machining defects and less visible peaks of waviness. According to Manuel et al. (2015), industry grading and sorting procedures are in many cases based on technical parameters which do not necessarily reflect the consumer preferences. However, all of these studies proved that the information about consumers’ perception is essential for the wood products industry.

So, in our study, we decided to work under industrial conditions, in collaboration with an interior joinery company (Rozière in Bozouls, France), in order to guarantee the reproducibility of all the tests conducted and to facilitate the transfer of the research findings to users. Three objectives were defined: (i) to clearly identify roughness parameters that allow raised grain to be objectively characterised on beech and oak wood surfaces finished with a waterborne varnish, (ii) to define a finished surface quality acceptable to consumers and industrials and (iii) to identify cutting conditions that generate low raised grain and an acceptable finished surface quality in order to eliminate the denibbing operation. Three hypotheses were proposed: (H1) raised grain is explained by the same roughness parameters regardless of the wood species, (H2) industrials are stricter than consumers when assessing the surface quality and (H3) there is a planing and/or a sanding condition that produces a finished surface quality that is acceptable to consumers without the denibbing operation being required.

## 2 Material and methods

### 2.1 Specimen preparation

Two hardwood species native to the Occitanie region of France were used. The first, pedunculate oak (*Quercus robur* L.) is a ring-porous wood species widely used for

manufacturing interior doors. According to the Rozière company, which supplied the wood used here, the oak surface shows significantly raised grain after the application of a waterborne varnish. The wood was used with a moisture content of  $10 \pm 1\%$  in the present research, after drying in a typical tunnel industrial dryer and stored at ambient temperature in the industry's dedicated storage room. The second, Pyrenees beech (*Fagus sylvatica* L.) is a diffuse porous wood species. It is abundant but under-exploited in the region, where it could constitute a valuable resource. The beech wood was supplied by a local sawmill, with a moisture content of  $13.7 \pm 1\%$  after drying in a typical tunnel industrial dryer. Density was measured on woods with 12% moisture content after conditioning at 20 °C and 65% relative humidity. Even though it may seem surprising that the Pyrenees beech and oak woods used in this work had almost the same density,  $0.75 \pm 0.02 \text{ g cm}^{-3}$  and  $0.75 \pm 0.01 \text{ g cm}^{-3}$ , respectively, their densities are in accordance with those found in literature (CIRAD 2015). Samples were taken from different boards from different trees for each species.

## 2.2 Machining treatment

The machining processes were those used by Rozière before the application of varnish, namely planing and sanding. The objective was to generate all possible levels of raised grain on the specimen surfaces, so the cutting conditions were adapted in order to produce surface qualities ranging from very rough to very smooth. To this end, levels of machining parameters were chosen that were beyond those already used in the literature (within the limits of our industrial partner's machine). We decided to consider three levels per modifiable machining parameter: the maximum and the minimum possible levels and the median level.

Planing was done with a WEINIG U 2000 planer, equipped with a two-straight-knife cutter head having a diameter of 100 mm, a 55° knife angle and a 10° rake angle. The machining parameters  $V_f$  (feed speed) and  $N$  (rotation speed) were considered because they were easy to modify and are known for their strong effects on the quality of machined wood surfaces (Ramanakoto et al. 2017). The levels chosen for  $V_f$  and  $N$  (Table 1) gave an average chip thickness,  $em$ , ranging from 0.07 to 0.4 mm, i.e. characteristic of surface qualities ranging from rough to very smooth (INRS 2001). A down-milling cutting mode was considered since it is generally used in industry—mainly for security reasons (Khazaeian 2006). The cutting directions were chosen arbitrarily according to the planks available: a longitudinal-radial,  $LR$  plane, a longitudinal-tangential,  $LT$  plane, or an intermediate plane. Indeed, according to Ramanantoandro et al. (2017), the cutting directions had no significant effect on the occurrence of raised grain on beech woods. The depth of cut was that used by the company, i.e. 2.5 mm.

Sanding was performed along the wood grain with a DMC Polisand belt sander from SCM France. The depth of cut was 0.5 mm and the belt rotation speed was  $20 \text{ m s}^{-1}$  for all the sandpapers. The sanding parameters considered were feed speed,  $V_f$ , and grit size. Again, three levels were used for each parameter (Table 1). For information, a  $V_f$  of  $8 \text{ m min}^{-1}$  and a sanding programme of P80-120-150-180 are currently used by our industrial partner to sand the surfaces before the application of varnish. We kept almost the same sanding programme, removing only the P150 paper as the literature recommends making at least one jump of grit size to obtain a difference in roughness (Hendarto et al. 2004). Moreover, to the best of our knowledge, no previous research has studied the difference of finishing performance between the various programmes.

For each machining process, the combination of two machining parameters at three levels yielded  $3^2$  experiments. The woods were thus machined with nine sanding cutting conditions and nine planing cutting conditions for each species. In total, 36 different surface qualities were obtained.

For this study, each cutting condition was performed on two different boards. The first board was varnished with denibbing between the two coats and the second was varnished without denibbing, to consider the influence of this operation during the visuo-tactile assessment of the surface quality. Thus, we obtained 36 non-denibbed and 36 denibbed finished surfaces of oak and beech wood. Denibbing was carried out under Rozière's usual operating conditions, i.e. manually by a specialised operator, with P240 sand-paper.

## 2.3 Measurement of topographic parameters on varnished surfaces of oak and beech

In the present study, topographic parameters were measured on two types of surface:

- (i) Surface after the application of the first coat of varnish, called S1, in order to identify the roughness parameters explaining the occurrence of raised grain. Eighteen planed and sanded surfaces of oak and 18 surfaces of beech were studied, with three replicates of the measurement for each surface, which gave a total of 108 measurements of the topographic parameters on S1 surfaces;
- (ii) Surface after the application of the second coat of varnish without denibbing, called S2, to determine the finished surface quality acceptable to consumers if the denibbing operation was not performed. As before, 108 measurements of topographic parameters were also made.

Thus, a total of 216 measurements of topographic parameters were completed. We used a large number of surface topographic parameters to be as exhaustive as possible. Seventeen roughness parameters were studied (on S1 and S2 surfaces):

**Table 1** Experimental design for machining the surface of beech and oak wood before finishing

Ech	Planing				Sanding	
	Vf (m min <sup>-1</sup> )	N (rpm)	em (mm)	fz (mm/tooth/rev)	Grit size	Vf (m min <sup>-1</sup> )
1	8	6000	0.11	0.67	P80	3
2	8	9000	0.07	0.44	P80	10
3	8	12,000	0.05	0.33	P80	18
4	19	6000	0.25	1.58	P80-120	3
5	19	9000	0.17	1.06	P80-120	10
6	19	12,000	0.13	0.79	P80-120	18
7	30	6000	0.40	2.50	P80-120-180	3
8	30	9000	0.26	1.67	P80-120-180	10
9	30	12,000	0.20	1.25	P80-120-180	18

Ech N° attributed to each surface according to the experimental design, Vf feed speed, N rotation speed, em average chip thickness, fz feed rate per tooth

sRa, sRq, sRp, sRv, sSk, Sku, Sk, Spk, Svk, Smr1, Smr2, Sdr, Sdq, Vvv, Vvc, Vmp, Vmc and 4 waviness parameters (only on S2, since waviness cannot be linked with raised grain): sWa, sWq, sWp, sWv, described in ISO 25178-2 (2012). The ISO 25178-2 (2012) standard uses S\* both for roughness and waviness parameters. In our study, we decided to distinguish the roughness parameters with “R” and the waviness parameters with “W”, for four parameters that are used to describe roughness as well as waviness: Sa, Sq, Sp and Sv.

These parameters were measured with an optical 3D ALICONA device (InfiniteFocusSL model). For each machining condition, a surface area 100 mm long (L) × 100 mm wide (T) was analysed. Topographic parameters were measured on three sampling areas of 8 mm (L) × 16 mm (T) on each surface, to better represent the surface, with a step of 1.3 μm. For the measurement of roughness parameters, cut-off lengths of 0.8 mm for beech and 2.5 mm for oak gave good representations of the roughness profiles according to Khazaeian (2006). For waviness parameters, a cut-off of 2.5 mm was considered for both species. Gurau et al. (2006) recommended as well the cut-off length of 2.5 mm on oak to overcome the effect of large pores. A Gaussian phase correct filter, the only available filter in the ALICONA optical instrument software, was applied for calculations (ISO 16610-21 2011 and ISO 16610-61 2015). Parameters were measured across the grain to take account of surface heterogeneity.

## 2.4 Characteristics of the coating product used

After machining, surfaces were directly varnished under the usual industrial operating conditions. The finishing product used was an AR6\*\*/00 Sayerlack water-based varnish. Two coats of varnish were applied to the surfaces within 1 h after machining at a spread rate of 60 g m<sup>-2</sup> per coat. The varnish was applied by a robot on an automated production line and

dried with UV lamps (E54 120 W cm<sup>-1</sup> at 420 nm) at 55 °C. The pause time between the two coats was about 20 min.

## 2.5 Visuo-tactile analyses

### 2.5.1 Assessment of raised grain on S1 surfaces

Raised grain was assessed on S1 surfaces with visuo-tactile analysis carried out by two Rozière employees responsible for the finishing department and two wood science researchers. Raised grain did, indeed, occur after the application of the first coat of varnish, obliging the manufacturer to perform the denibbing operation. The oak and beech wood surfaces, having dimensions 150 mm (L) and 100 mm (T), were presented separately to avoid comparison between the two species, which had different surface textures. Planed and sanded surfaces were mixed together. Surfaces were presented randomly and in a monadic way.

The four judges were asked to observe and touch the surfaces without any particular restrictions, whether the surface had to be denibbed or not, and to rate surfaces on a 5-point scale, on which levels 1 and 2 were arbitrarily defined as acceptable (very low and low raised grain, RF, respectively), and 3, 4, 5 as not acceptable (RF very pronounced) and requiring denibbing.

### 2.5.2 Assessment of finished surface quality on S2

Visuo-tactile analyses were conducted with 62 consumers (standard ISO/DIS 11136: 2013) and two industrial participants to evaluate and compare their appreciations of the finished surface quality S2. The consumer panels were selected to represent the French population in the Occitanie Region. For this purpose, the criteria “age” and “sex” were considered. According to the French national statistics bureau, INSEE (2014), this region has 48.4% of men and 51.6% of women. The population is divided into three groups of age: 28.6% are

between 0 and 24 years old, 44.2% between 25 and 59 years old and 27.2% over 60 years old. We followed these proportions as well as possible and the 62 participants were selected as follows: 30 men and 32 women; 19 for the first age group, 40 for the second, and 3 for the over-60 age group, which was therefore under-represented in this study.

The tests were conducted in a room lit by natural daylight to reproduce the purchasing conditions, and in a sitting position with an individual seat as in a standard sensory analysis laboratory. All test samples were placed on a table, where 72 non-denibbed and denibbed finished surfaces of oak and beech woods, 50 mm (L) × 50 mm (T), were presented to each participant. The species were presented separately, but planed and sanded, denibbed and non-denibbed surfaces were mixed together, as consumers would be interested in the finished surface qualities regardless of how they were obtained. Each participant was asked to observe and touch the surface at the same time with the index, using a maximum of two return movements, i.e. following the wood grain and perpendicular to the wood grain. For the 62 participants, 6 specimens of each surface were produced, so that a surface was touched by 10 persons at most, the aim being to avoid surface wear influencing the appreciation of the surface quality. To avoid any psychological effect during the visuo-tactile tests, the wood samples were coded and classified with an equal chance of occurrence, using FIZZ software (Biosystem). The order of presentation of the samples was therefore different for each participant. The samples were presented in a monadic way.

Participants were asked to score their appreciation of the surface quality on a 9-point hedonic scale, where score 1 meant “I thoroughly dislike” and 9 meant “I like enormously”, and according to two criteria: preference with respect to surface roughness and with respect to surface waviness. This rating scale was chosen as it gave symmetrical scoring of the preference centred on the score 5. Thus, the latter was considered by consumers as a threshold of acceptable surface quality, above which they would be ready to buy a door of this surface quality. They were told that annual tree-rings, wood pores, colour and texture differences on surfaces should not be considered. For the participants from industry, the same approach was used. However, at the end of the visuo-tactile tests, they were asked to define the threshold score themselves, as the score above which they would be ready to sell a door with a defined surface quality, regardless of the mean score of 5. Their acceptability threshold was equal to 8 on a 9-point scale. This means that, even though some surfaces reached a score between 5 and 8, they were not considered to be of sufficient quality to be put on sale.

## 2.6 Statistical analysis

The XLSTAT 2018 and Minitab 17 software packages were used for statistical data processing. Descriptive analyses were

made on the visuo-tactile scores and the values of topographic parameters measured on surfaces S1 and S2. Principal component analyses (PCA) were conducted to establish links between visuo-tactile scores and topographic parameters. Using linear regression [visuo-tactile scores =  $f$ (topographic parameters)], the thresholds of the topographic parameters giving an acceptable level of raised grain (score  $\leq 2$ ), and defining a finished surface quality acceptable to consumers (score  $\geq 5$ ) and industrials (score  $\geq 8$ ) were calculated. This enabled consumers’ and manufacturers’ appreciations of the surface quality to be compared. An analysis of variance (ANOVA at the 5% significance level) and a correlation study were carried out between the machining parameters and the visuo-tactile scores to determine the cutting conditions that could possibly eliminate the denibbing operation and optimise finishing in the wood industry.

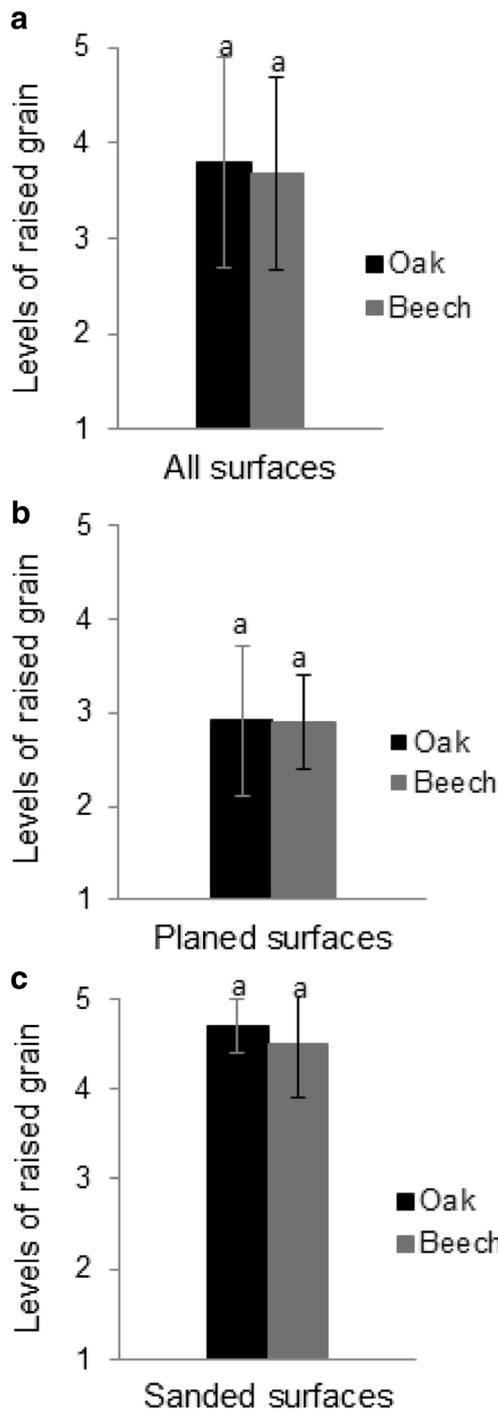
## 3 Results

### 3.1 Occurrence of raised grain on S1 surfaces varnished with one coat

According to the average visuo-tactile scores of industrial participants and wood researchers (experts), raised grain occurs significantly on both oak and beech surfaces regardless of the machining processes used (Fig. 1).

Regarding the machining processes, for both industrials and researchers, for both beech and oak woods, all sanded surfaces needed to be denibbed as they presented marked raised grain, i.e., with high occurrence frequencies of levels 3, 4 and 5, and no case of acceptable levels, i.e. less than or equal to 2 (Fig. 2a).

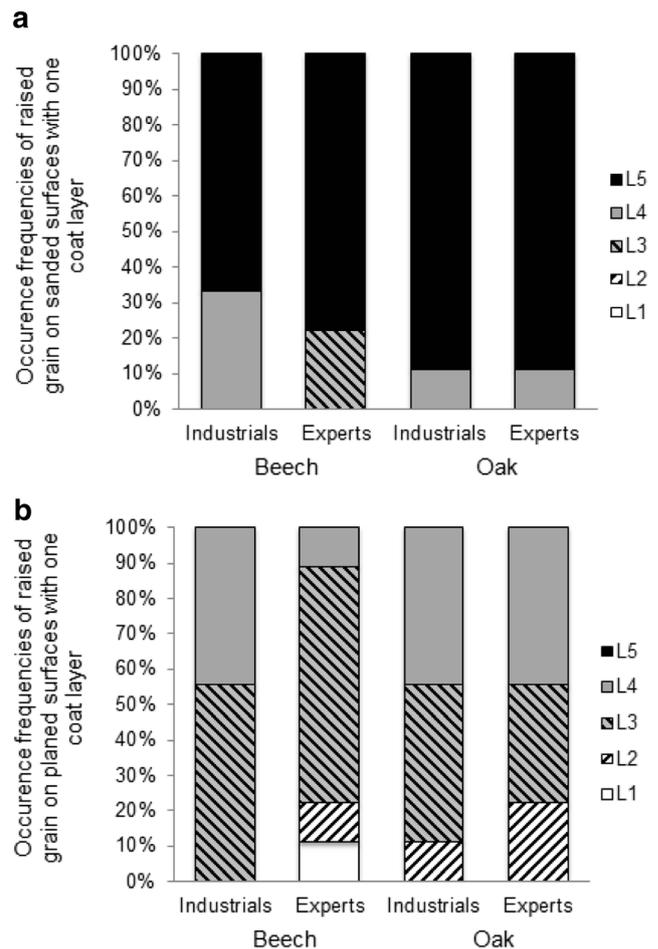
Raised grain was less pronounced on planed than on sanded surfaces (Fig. 2), which is entirely consistent with results found in the literature (Ramanantoandro et al. 2017). According to industrials, beech surfaces presented only unacceptable raised grain with levels 3 and 4 (Fig. 2b). Therefore, they must be denibbed. However, for research experts, some planed surfaces of beech (22% of all surfaces studied) had low levels of raised grain (levels 1 and 2). This difference demonstrates that industrials overestimate the surface quality required by consumers and confirms the need to determine a threshold for an acceptable surface quality, in order to direct the production processes towards the preferences of the consumers, like stated Manuel et al. (2015). On planed surfaces of oak, this difference of appreciation was again noted. Nevertheless, both industrial and research experts agreed that some surfaces presented low raised grain (11% of surfaces studied for industrials and 22% for researchers), i.e. did not require denibbing.



**Fig. 1** Levels of raised grain according to the average visuo-tactile scores of industrial and research experts for S1 surfaces varnished with one coat, according to tree species and machining processes. Letter “a” indicates significance of differences at 5% level (ANOVA)

### 3.2 Roughness parameters characterising the visuo-tactile sensation of raised grain on S1 surfaces

The average values of the topographic parameters measured on all S1 surfaces (sanded and planed surfaces considered)

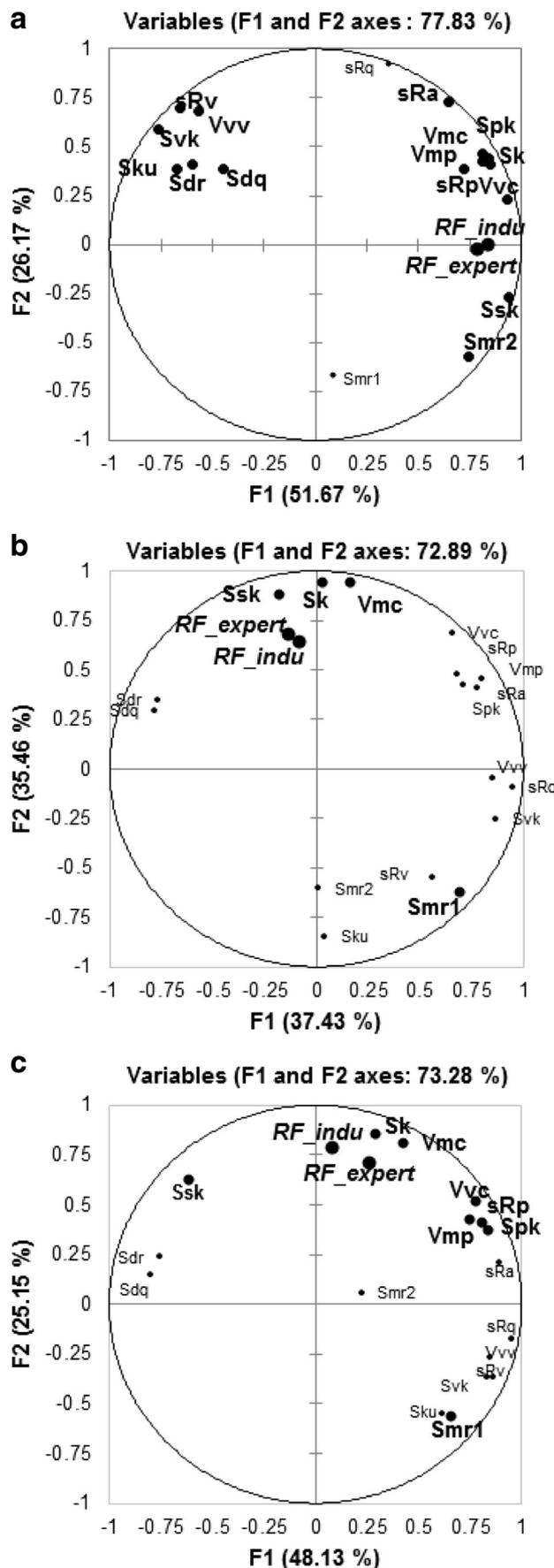


**Fig. 2** Occurrence frequencies of raised grain on S1 surfaces varnished with one coat: **a** sanded surfaces; **b** planed surfaces (L1 to L5: level 1 acceptable surface to level 5 unacceptable surface)

and the average values of the visuo-tactile scores measured on each surface (data available in Ramanakoto et al. 2018) were analysed using principal component analysis (PCA) (Fig. 3), to determine if there are significant correlations between these variables, for each species (Fig. 3a, b), and by considering both species together (Fig. 3c).

Variables that are close to the periphery of the circle and one of the axes are well explained by these axes. The closer two variables are in the PCA plot, the stronger is their link. Variables in the same plane are positively correlated, and in the opposite plane are negatively correlated. The two principal components (F1 and F2 axes) accounted for more than 70% of the total variance in the data set. Therefore, in these cases, they represented well the correlation information between variables.

When the values of *sRa* roughness parameters measured on S1 surfaces were examined for each species, the oak surface (*sRa* ranging from 7 to 19  $\mu\text{m}$ ) is generally rougher than that of beech (*sRa* ranging from 6 to 10  $\mu\text{m}$ ) (data available in Ramanakoto et al. 2018), as a result of the porous surface of oak (Leclercq 1993). However, a large number of parameters were correlated with the visuo-tactile sensation of raised grain



◀ Fig. 3 Correlation mapping showing the relationship between raised grain and roughness parameters: *RF\_indu*: industrial's scores of raised grain; *RF\_expert*: research experts' scores of raised grain; small font size: parameters not correlated with scores; large font size: parameters correlated with scores; **a** beech; **b** oak; **c** both species

for beech (15 of the 17 measured roughness parameters) (Fig. 3a). On oak, few parameters were significantly correlated with the visuo-tactile scores (Fig. 3b). This demonstrates that not only the touch can feel the surface roughness generated by the different cutting conditions used, but it can also really feel the occurrence of raised grain, especially for the case of the oak surface. On a uniform surface of beech, the occurrence of raised grain generally increases the tactile sensation of surface roughness. Thus, a lot of parameters had correlations with the visuo-tactile scores. However, on oak, the tactile sensation of raised grain was softened because of the wood's surface heterogeneity, with naturally porous and highly textured surfaces. Hence, the few correlated parameters found on oak were directly linked with the tactile sensation of raised grain, not the roughness due to the machining process or the wood anatomy.

By comparing the parameters correlated with raised grain for each wood species (Fig. 3a, b) and when carrying out a correlation analysis by mixing the two species (Fig. 3c), we discovered that *Sk* (core height, i.e. the distance between the highest and lowest level of the core surface), *Vmc* (core material volume) and *Ssk* (skewness of the amplitude distribution curve of surface topography referring to midline) were the only parameters always correlated with the visuo-tactile scores. Therefore, these parameters really explain raised grain regardless of the wood anatomy of the two species studied. Gurau and Irlé (2017) reported the importance of the Abbot-Firestone curve parameters, such as *Sk*, to differentiate the processing roughness from anatomical roughness. The occurrence of raised grain is then together justified by the tactile sensation of protruding peaks ( $Ssk > 0$ ) and a certain amount of material in the core of the roughness profile (*Sk*, *Vmc*).

On beech surfaces, the negative correlation between raised grain and parameters describing the voids and the proportion of reliefs (*Vvv*-dale void volume, *sRv*-maximum pit height, *Svk*-average height of the protruding dales below the core surface, *Sdq*-slope of reliefs, *Sdr*-proportion of reliefs) justified the fact that fibres raise but do not leave deep furrows on the surface. Valleys created were just located below the core of the roughness profile and were not very deep. Therefore, raised grain only affects parameters located at the core and the peak zones of the roughness profile.

### 3.3 Surface quality acceptable to consumers and industrial without denibbing operation

The visuo-tactile analysis was carried out on all denibbed and undenibbed finished S2 surfaces, regardless of the machining

processes used. However, in the following analyses, only undeniably finished surfaces are considered in order to determine whether an acceptable finished surface quality for consumers and industrials can be found without going through the denibbing operation.

Smooth surfaces (low values of roughness parameters) were generally appreciated by both industrials and consumers (Fig. 4). On oak surfaces, deep valleys justifying the presence of vessels were appreciated by industrials (positive correlation between industrials' scores and parameters describing the valleys Sv<sub>k</sub>, sR<sub>v</sub>, V<sub>vv</sub>-void volume), but not by consumers, for whom the wood anatomy was perceived as a roughness defect on oak surfaces (Fig. 4b).

Raised grain influenced the appreciation of finished surfaces. The parameters Sk, V<sub>mc</sub> and S<sub>sk</sub> explaining the occurrence of raised grain on S1 surfaces described in Sect. 3.2 were also correlated with the preference scores of undeniably finished surfaces (Fig. 4). Observing the correlation between the scores attributed to the S2 finished surfaces and those attributed to the S1 varnished surfaces for the two species, it can be seen that the higher the raised grain occurring on S1 was, the less the quality of finished surfaces S2 would be appreciated (Fig. 5), especially by industrials (Fig. 5b). For a score of 5/10, the threshold of an acceptable finished surface on S2 for consumers, there were seven (6 on oak and 1 on beech) undeniably finished surfaces accepted (Fig. 5a), whereas, for a score of 8/10, the threshold of an acceptable finished surface for industrials, only four (on oak) of the seven undeniably finished surfaces accepted by consumers were considered acceptable by industrials (Fig. 5b). This again confirms the industrials' overestimation of the surface quality required.

Although raised grain influenced the appreciation of the finished surfaces, it is surprising to note that some surfaces with unacceptable raised grain on S1 (levels of raised grain higher than 2) were accepted on S2 (Fig. 5). These findings reveal that the thresholds of surface parameters defining an acceptable raised grain must be defined on S2 as the assessment of raised grain on S1 cannot fully predict the quality of finished surfaces obtained on S2.

### 3.4 Thresholds of topographic parameters for acceptable quality of undeniably finished surfaces

Only parameters correlated with the visuo-tactile sensation of raised grain and significantly correlated with the preference scores at the 5% significance level were considered (Table 2). Thresholds for other parameters are presented in Ramanakoto (2017).

For beech, the thresholds of parameters for industrials are lower than for consumers. However, we found the opposite case with oak. Therefore, industrial participants were stricter than consumers when assessing the quality of

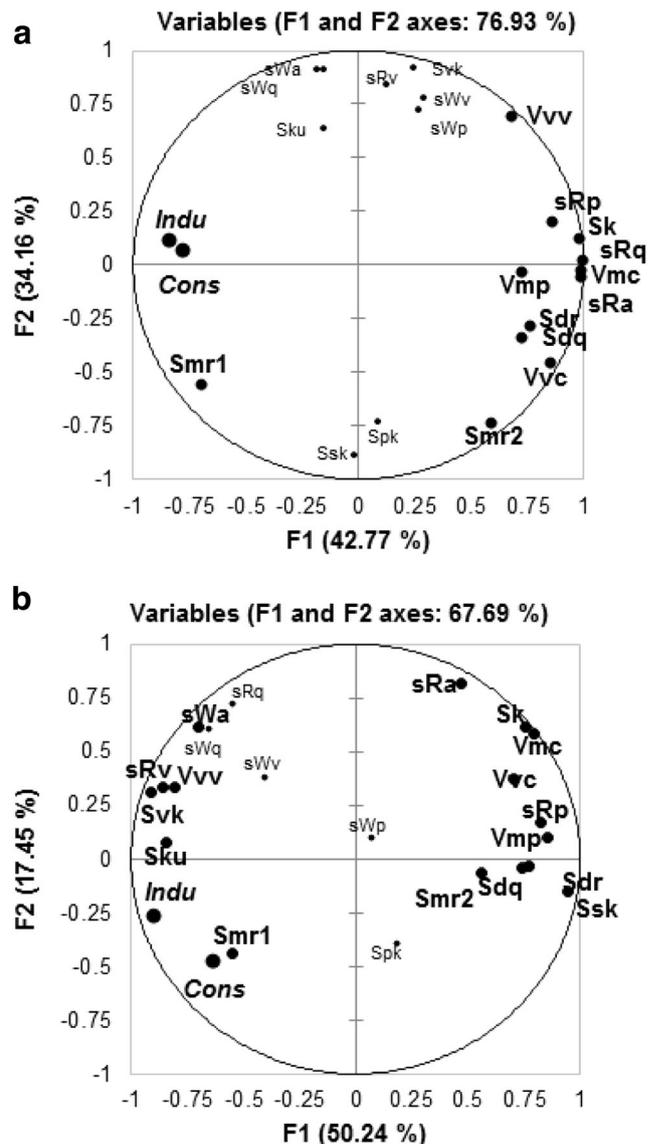
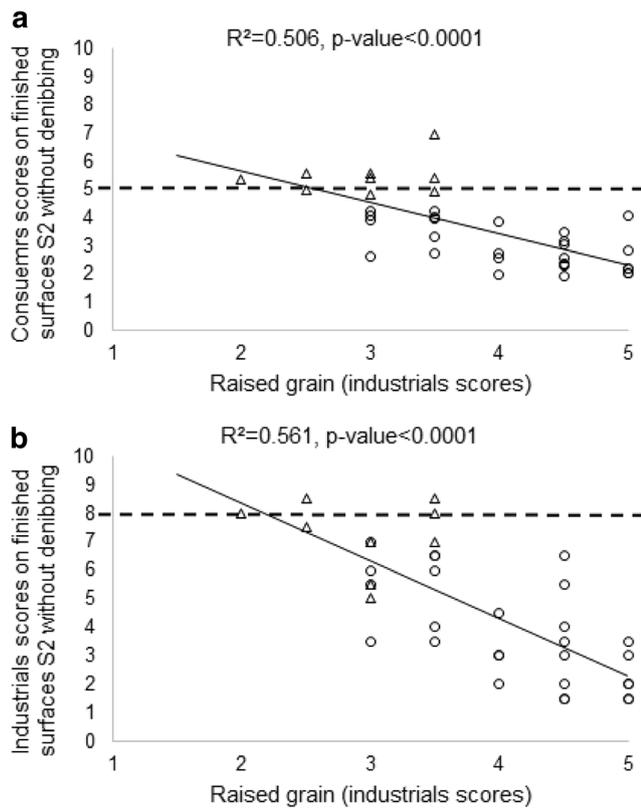


Fig. 4 Correlation mapping showing the relationship between preference scores of surface quality (planed and sanded mixed) and topographic parameters: Indu: industrials' scores; Cons: consumers' scores; small font size: parameters non-correlated with scores; large font size: parameters correlated with scores; a beech; b oak

finished surfaces of beech wood with a homogeneous surface, while consumers did not tolerate roughness on heterogeneous oak surfaces. As already stated in Sect. 3.3 (Fig. 4b), anatomy of oak wood was perceived as a roughness defect by consumers.

Comparing the two wood species, thresholds of all parameters were lower for beech than for oak. So, surfaces of beech must be smoother than surfaces of oak to be appreciated by both consumers and industrials. Thus, on a homogeneous wood surface with small vessels, such as for beech, surface defects and raised grain are easily detectable and require more attention from industrials when machining the surface.



**Fig. 5** Linear correlation between raised grain obtained on S1, and visual-tactile preferences of finished surfaces obtained on S2: **a** for consumers; **b** for industrialists; triangle: surface qualities accepted by consumers

### 3.5 Cutting conditions that generate an acceptable finished surface quality without denibbing

On S1 surfaces, as we saw in Sect. 3.1, only planed surfaces of oak had an acceptable raised grain (levels 1 and 2) for both consumers and industrialists. Thus, all beech surfaces and all sanded surfaces must be denibbed as they always present marked raised grain. Therefore, it is better to use cutting conditions that speed up production.

If we focus our analysis on oak only, the effect of planing parameters on the occurrence of raised grain on S1 surfaces gives an understanding of how the increase of  $V_f$ , and its interaction with the rotation speed,  $N$ , (characterising the feed rate per tooth,  $f_z$ , and the average chip thickness,  $em$ ), favour the occurrence of raised grain (Fig. 6). Overall, it is then necessary to use a  $V_f$ , combined with a high  $N$  to obtain a low  $f_z$  (Fig. 6a) and a low  $em$  (Fig. 6b), to generate low raised grain.

Although the coefficient  $R^2$  in Fig. 6 is low (Bosquet 2006), the correlation is significant. From this analysis, the most important was to find the trend of the relationship existing between consumer and industrial scores on raised grain and machining parameters. The thresholds of  $f_z$  and  $em$  giving acceptable raised grain (level  $\leq 2$ ) were then calculated (Ramanakoto 2017). Nevertheless, considering the thresholds obtained from the proposed models ( $f_z1 \leq -0.4$  mm/tooth/rev,  $em1 \leq -0.064$  mm), it is impossible to obtain values of  $f_z$  and  $em$  that generate acceptable raised grain, since the thresholds correspond to a negative value (which is physically impossible). The thresholds of parameters were determined from the analysis on finished surfaces.

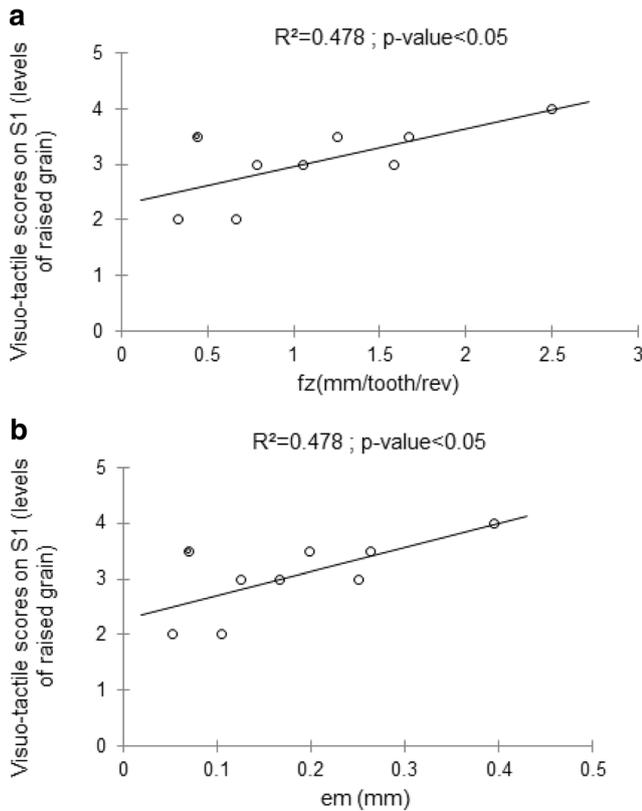
On S2 surfaces of oak, six planed cutting conditions gave acceptable finished surfaces on oak without denibbing (average scores above the acceptability thresholds) for consumers and four gave acceptable results for industrialists (Figs. 5 and 7). The four surfaces appreciated by both industrialists and consumers were surfaces no 1, 2, 3 and 9 according to the experimental design (Table 1). Those only appreciated by consumers were surfaces no 5 and 6.

In order to establish an abacus of optimal cutting conditions and to determine thresholds of cutting parameters from which it is no longer necessary to perform a denibbing operation to obtain a surface quality acceptable to consumers on oak, we identified the planing parameters correlated with consumers' scores on S2. Like the results obtained on S1, the feed rate per tooth,  $f_z$ , and the average chip thickness,  $em$ , are significantly correlated with consumers' scores (Fig. 8).

**Table 2** Thresholds of topographic parameters to define acceptable finished surface quality for consumers and industrialists (planed and sanded surfaces mixed together)

		For consumers			For industrialists		
Beech	Parameters	Equations	$R$	$NG \geq 5/10$	Equations	$R$	$NI \geq 8/10$
	Sk ( $\mu m$ )	$NG = 6.68 - 0.13 * Sk$	-0.67*	$Sk \leq 12.92$	$NI = 10.37 - 0.25 * Sk$	-0.76**	$Sk \leq 9.48$
	$V_{mc}$ ( $ml/m^2$ )	$NG = 8.16 - 0.5 * V_{mc}$	-0.7*	$V_{mc} \leq 6.32$	$NI = 13.19 - 0.94 * V_{mc}$	-0.78**	$V_{mc} \leq 5.52$
Oak	Sk ( $\mu m$ )	$NG = 8.75 - 0.18 * Sk$	-0.75***	$Sk \leq 21.42$	$NI = 14.36 - 0.33 * Sk$	-0.83***	$Sk \leq 28.57$
	Ssk (-)	$NG = 3.14 - 0.44 * Ssk$	-0.51*	$Ssk \leq -4.27$	$NI = 3.29 - 1.13 * Ssk$	-0.79***	$Ssk \leq -1.52$
	$V_{mc}$ ( $ml/m^2$ )	$NG = 10.68 - 0.65 * V_{mc}$	-0.76***	$V_{mc} \leq 8.73$	$NI = 18.12 - 1.23 * V_{mc}$	-0.85***	$V_{mc} \leq 10.65$

Thresholds for an acceptable surface quality: 5/10 for consumers, 8/10 for industrialists; NG: consumers' scores; NI: industrialists' scores.  $R$ : correlation coefficient; \*\*\*significant at 0.1% level; \*\*significant at 1% level; \*significant at 5% level

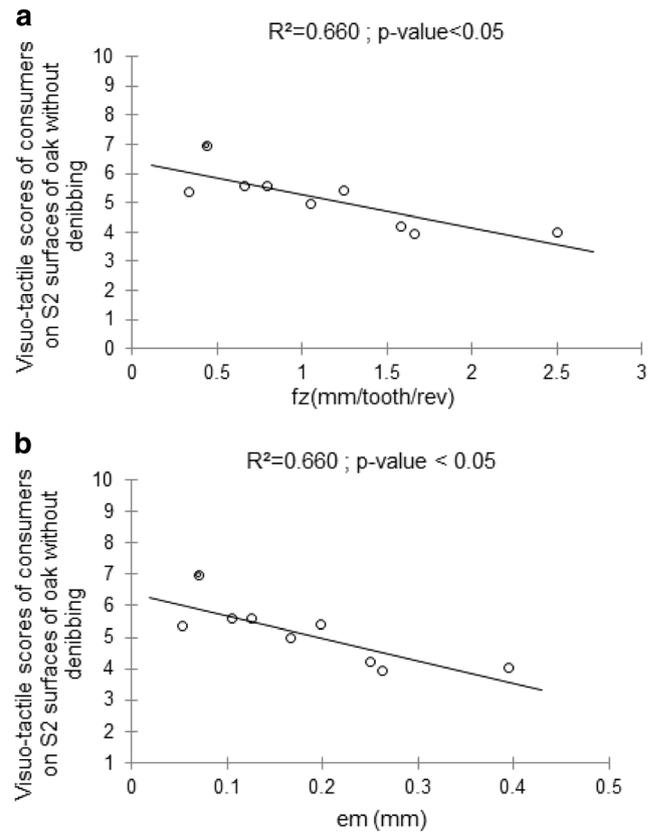
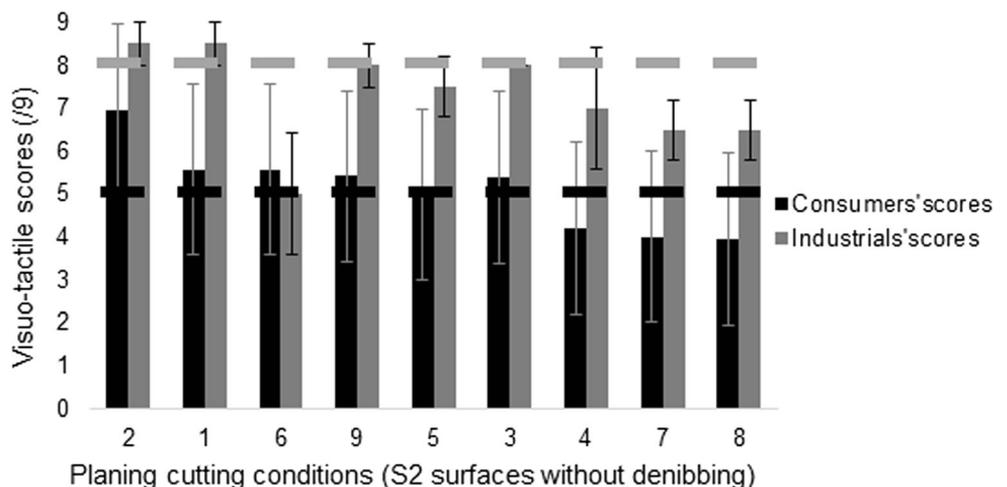


**Fig. 6** Effect of feed rate per tooth,  $fz$ , and average chip thickness,  $em$ , on raised grain on planed S1 surfaces of oak (raised grain represented the average visuo-tactile scores of industrials and research experts on S1)

The calculated thresholds show that it is necessary to use cutting conditions that provide a feed rate per tooth,  $fz$ , of less than 1.248 mm/tooth/rev and an average chip thickness,  $em$ , less than 0.197 mm to generate a finished surface quality of oak acceptable to consumers without denibbing (Table 3).

From these thresholds, it was possible to establish an abacus defining the acceptable cutting zone on planing (Table 4).

**Fig. 7** Average visuo-tactile scores of the planed finished surfaces of oak without denibbing for consumers and industrials. Scores are ranked in decreasing order of the consumers' scores: comparable scores defining acceptability thresholds of surface quality: black dashes for consumers (5/10) and grey dashes for industrials (8/10); error bar: standard deviation.



**Fig. 8** Significant correlation between **a** the feed rate per tooth,  $fz$ , **b** the average chip thickness,  $em$ , and consumers' scores on S2 surfaces of oak

## 4 Discussion

### 4.1 Occurrence of raised grain depending on machining processes

Raised grain is more pronounced on sanded surfaces than on planed surfaces. Ramananantoandro et al. (2017) and Hernández and Cool (2008) found the same result. These

**Table 3** Correlation showing the effect of the planing factors on the visuo-tactile scores of consumers on S2 surfaces of oak

		Threshold for NG = 5
fz (mm/tooth/rev)	NG = 6412–1131*fz	$fz_2 \leq 1.248$
e <sub>m</sub> (mm)	NG = 6412–7156*em	$em_2 \leq 0.197$

Threshold for an acceptable surface quality: 5/10 for consumers; fz: feed rate per tooth; em: average chip thickness

authors linked raised grain with the degree of fibrillation, which occurs as the partial or total detachment of microfibrils or groups of fibrils from the cell walls. On sanded surfaces, cell-wall fibrillation is more severe because of the redundancy of the sanding process (de Moura et al. 2010), which produces severe damage and detachment of the cell walls (Sulaiman et al. 2009). After the application of a waterborne varnish, the group of fibrils detached from the cell walls swells by water-soaking. This causes them to separate and to rise in large quantities (Ramanantoandro et al. 2017). For planing, the knife removes materials by producing wood chips, so the level of fibrillation on planed surfaces is lower and produces less raised grain than on sanded surfaces.

According to Stewart (1980), fuzzy grain is often associated with some of the factors that cause raised grain. Fuzzy grain is fibres or groups of fibres that have not been cleanly severed by machining and stand up above the surface. Fuzzy grain is generally associated with abnormal wood of gelatinous fibres that shrink and swell more than normal wood with changes in moisture content. De Moura and Hernandez (2006) stated clearly that cell-wall fibrillation cannot be considered as machining defect, i.e. fuzzy grain. The fuzzy texture is due to the cell-wall fibrillation.

For sanding, Evans et al. (2017), who modelled the action of abrasives on wood cell walls, pointed out that the significance of raised grain, evaluated for these authors with the *Sa* roughness parameter, was correlated with the coarseness of the abrasive. According to them, raised grain can be reduced in severity by tailoring sanding to account for the density and surface microstructure of the wood. It would be interesting to carry out a study in this direction by testing several grit sizes of abrasive on several wood species with different densities, and really assessing the importance of raised grain by visuo-tactile analysis.

#### 4.2 Topographic parameters explaining the tactile sensation of raised grain and describing an acceptable finished surface quality

In the previous section, the relationship between raised grain and the degree of fibrillation was discussed. We attempted to verify this relationship by analysing the parameters explaining the occurrence of these two phenomena. De Moura and Hernandez (2006) and Cool and Hernandez (2011) linked

fibrillation with the sRp and Spk roughness parameters (height of protruding peaks) measured on uncoated, machined surfaces. In the present study, these parameters were correlated with raised grain on varnished surfaces of beech but not oak. These results suggest that fibrillation could contribute to raised grain on wood surfaces, but these two phenomena were not necessarily represented by the same roughness parameters as fibrillation is observed microfibril scale with a section diameter between 2 and 6  $\mu\text{m}$  (Lambillon et al. 2013). With fibrillation, we can detect only the peaks on the surface, while for raised grain, the fibres that rise are millimetric and create not only a tactile sensation of preponderant peaks (Ssk) on the surface but also a certain amount of material in the core of the roughness profile (Sk, Vmc).

Discussion can be raised on the reability of the measurement of roughness parameters regarding the filtering method used in our study. Indeed, Gurau et al. (2006) recommended that Robust Gaussian Regression filter is suitable for wood surfaces, as it is less likely to introduce distortion of the roughness profile than the standard Gaussian filter. For wood species having group of deep pores, Piratelli-Filho et al. (2012) recommended the use of three filters to obtain the exact roughness profile of the surface. The filters used were polynomial regression and robust Gaussian regression filter to address and reduce the variation attributed to the form and waviness, and Abbot curve filter to extract the deepest valleys in the profile associated with anatomy of materials like wood. Although these methods of filtering suggested above are interesting, it was not possible to apply them in our work. The existing filter in the ALICONA device was the Gaussian phase correct filter (described in ISO 16610-21 2011/ISO 16610-61 2015). The standard Gaussian filter shows an offset which induced overemphasised peaks around valleys and an underestimation of the depth. The correct phase Gaussian filter implemented in the ALICONA device was adapted to avoid this problem. This type of filter does not produce distortion of the profile compared to the standard Gaussian filter. As a result, it faithfully reproduces the amplitude of the primary profile. Moreover, the optical measurement device InfiniteFocus by Alicona generates very few discontinuities as it measured a 3D dataset using the focus variation technology, and the larger amount of data used for calculation gives representative and repeatable results (Danzl et al. 2008).

Parameters correlated with raised grain that we found in our study were compared with the results of other researchers. Ramanantoandro et al. (2017) found that sRa, sRq, Spk and Vmp were correlated with raised grain on planed and sanded surfaces of beech. In our study, too, the parameters sRa, Spk and Vmp were significantly correlated with visuo-tactile scores on beech surfaces, but not on oak surfaces. It can be then concluded that these parameters are not always representative of raised grain. They actually reflect the tactile sensation of roughness on a homogeneous surface of beech, but do not

**Table 4** Abacus defining cutting conditions for planing giving a surface quality of oak acceptable to consumers without denibbing operation

N (rpm)	Vf (m min <sup>-1</sup> )											
	8	9	10	11	12	13	14	15	16	17	18	19
6000	0.11 (0.67)	0.12 (0.75)	0.13 (0.83)	0.14 (0.92)	0.16 (1)	0.17 (1.08)	0.18 (1.17)	0.2 (1.25)	0.18 (1.14)	0.19 (1.21)	0.18 (1.13)	0.19 (1.19)
7000	0.09 (0.57)	0.1 (0.64)	0.11 (0.71)	0.12 (0.79)	0.14 (0.86)	0.15 (0.93)	0.16 (1)	0.17 (1.07)	0.16 (1)	0.17 (1.06)	0.16 (1)	0.17 (1.06)
8000	0.08 (0.5)	0.09 (0.56)	0.1 (0.63)	0.11 (0.69)	0.12 (0.75)	0.13 (0.81)	0.14 (0.88)	0.15 (0.94)	0.14 (0.89)	0.15 (0.94)	0.14 (0.89)	0.15 (0.95)
9000	0.07 (0.44)	0.08 (0.5)	0.09 (0.56)	0.1 (0.61)	0.11 (0.67)	0.11 (0.72)	0.12 (0.78)	0.13 (0.83)	0.13 (0.8)	0.13 (0.85)	0.14 (0.9)	0.15 (0.95)
10,000	0.06 (0.4)	0.07 (0.45)	0.08 (0.5)	0.09 (0.55)	0.09 (0.6)	0.1 (0.65)	0.11 (0.7)	0.12 (0.75)	0.13 (0.8)	0.13 (0.85)	0.14 (0.9)	0.15 (0.95)
11,000	0.06 (0.36)	0.06 (0.41)	0.07 (0.45)	0.08 (0.5)	0.09 (0.53)	0.09 (0.6)	0.1 (0.64)	0.11 (0.68)	0.11 (0.73)	0.12 (0.77)	0.13 (0.82)	0.14 (0.86)
12,000	0.05 (0.33)	0.06 (0.38)	0.07 (0.42)	0.07 (0.46)	0.08 (0.5)	0.09 (0.54)	0.09 (0.58)	0.1 (0.63)	0.11 (0.67)	0.11 (0.71)	0.12 (0.75)	0.13 (0.79)

N (rpm)	Vf (m min <sup>-1</sup> )											
	20	21	22	23	24	25	26	27	28	29	30	
6000												
7000												
8000	0.2 (1.25)											
9000	0.18 (1.11)	0.18 (1.17)										
10,000	0.16 (1)	0.17 (1.05)	0.19 (1.22)									
11,000	0.14 (0.91)	0.15 (0.95)	0.16 (1)	0.18 (1.15)	0.19 (1.20)	0.2 (1.25)	0.19 (1.18)	0.19 (1.23)	0.18 (1.13)	0.18 (1.17)	0.19 (1.21)	0.2 (1.25)
12,000	0.13 (0.83)	0.14 (0.88)	0.14 (0.92)	0.15 (0.96)	0.16 (1)	0.16 (1.04)	0.17 (1.08)	0.18 (1.13)	0.18 (1.13)	0.18 (1.17)	0.19 (1.21)	0.2 (1.25)

The top numbers correspond to the average chip thickness, em, in mm, and the numbers in parentheses correspond to the feed rate per tooth, fz, in mm/tooth/rev

reflect the exact sensation of raised grain. Indeed, these parameters only describe the height of the protruding peaks above the core surface and the highest peaks. However for the case of raised grain, when fibres raise, they do not necessary produced the highest peaks on the surface. Moreover, the correlation found by Ramanantoandro et al. (2017) between these parameters and the tactile sensation of raised grain was only slightly significant. These authors did not find correlations with the Ssk, Vmc and Sk parameters that represent raised grain in our study. There could be two reasons for these results. First, few parameters were considered in their analyses (Vmc and Sk were not present). Secondly, Ssk was not correlated with raised grain, probably because of a lack of repetition in tactile analysis, which was carried out only by two experts.

According to Landry et al. (2013), raised grain on sanded surfaces of yellow birch was linked with parameters Sq and Sdr. These authors found a decrease in the values of the parameters after the application of a water-borne varnish and a solvent-based varnish. However, this decrease was less significant for the water-based varnish than for the solvent-based one, respectively, 15% and 36% for Sq and 50% and 70% for Sdr on solid wood. In our study, these parameters did not explain raised grain. Landry's findings differ from our results probably because they did not assess raised grain by a visuo-tactile analysis, but by observation of the global variation of the values of the parameters studied (Sq, Sp, Sv, Ssk, Sku, Sdr) before and after application of varnish, and they worked only on sanded surfaces. Moreover, they concluded that the parameters included both the overall roughness of the varnished surface and the roughness left by raised grain.

As we tried to study all topographic parameters as exhaustive as possible, we might have considered some parameters that could be interesting such as Sdc which describes the maximum height of the surface when the extreme peaks and valleys are removed; or the Sxp which describes the peak extreme height (Blateyron 2013). Nevertheless, these parameters describe only the upper part of the roughness profile, which can be assimilated with the Vmp, Sp and Spk parameters, that were not correlated with the tactile sensation of raised grain.

### 4.3 Importance of raised grain according to species

Thresholds of the roughness parameters explaining raised grain (Table 2) were lower for beech than for oak. The tactile sensation of raised grain on beech was probably more accentuated because of its homogeneous surface. Beech is a diffuse porous wood species, having a large number of vessels (50 to 100 per mm<sup>2</sup>), with a small diameter of the cell lumens ranging from 50 to 75 μm.

Oak is a ring-porous wood species, with large vessels in earlywood ranging from 300 to 500  $\mu\text{m}$  in diameter, and small vessels in latewood, up to 20  $\mu\text{m}$ . Thus, the larger vessel size in earlywood of oak results in a smaller proportion of fibres (Leclercq 1993). Moreover, thick fibres are found in latewood (Jacquiot et al. 1973 in Ghazil 2010). These anatomical singularities of oak could somewhat reduce the tactile sensation of raised grain.

The role of surface reactivity on raised grain has not been studied yet. Raised grain is undeniably related to the action of water on the wood surface. The information available in the literature on the reactivity of oak and beech wood surfaces indicates that oak surface tends to be hydrophobic due to the migration of tannins on the top surface (Bednar and Fengel 1974). Beech, on the other hand, contains very small amounts of hydrophobic compounds but has large quantities of polar molecules of monosaccharides (Zule and Moze 2003), leading to a hydrophilic surface. The hydrophobic characteristics of wood surface could have an impact on the degree to which the grain is raised. The hydrophilic surface of beech might be more sensitive to shrinkage and swelling of the wood fibres, and thus promote the occurrence of raised grain when a waterborne varnish is applied, especially when its moisture content (13.7%) was higher than for oak (10%) in our study. Moreover, in Ramanantoandro et al. (2017) study, the beech surfaces that were varnished only 48 h after machining may have become increasingly hydrophobic over time, thus reducing the swelling and lifting of fibres during the application of varnish. Therefore, it would be interesting to study the real impact of wood surface reactivity on raised grain in the future, for example by testing different surface treatment methods (chemical or thermal) prior to the application of a waterborne varnish.

Finally, our study was performed mainly under industrial conditions. For that reason, some experimental conditions were not optimum, such as the cutting direction of wood, the wood moisture contents of beech before machining and finishing processes. Thus, our result could have been impacted. The high moisture content of beech woods (13.7%) can explain why all beech surfaces presented marked raised grain and must be denibbed. Nevertheless, working under industrial conditions was essential for our works in order to guarantee the reproducibility of all the tests conducted and to facilitate the transfer of the research findings to industrials. Moreover, our work has contributed to broaden knowledge about the relationship between the 3D surface topography characteristics and the functionality of machined surfaces. We therefore answered one of the questions raised by Thibaut et al. (2016) about the identification of criteria that should be considered to define a finished surface quality acceptable to consumers, and the optimization of machining parameters according to these criteria.

## 5 Conclusion

Raised grain was explained by the same roughness parameters  $S_{sk}$ ,  $V_{mc}$  and  $S_k$  on planed and sanded surfaces of beech and oak (hypothesis H1 validated). The occurrence of raised grain on wood surfaces after the application of a waterborne varnish is justified by the tactile sensation of protruding peaks, and a certain amount of material in the core of the roughness profile. It is easily detectable on the homogeneous wood surface of beech. Industrials were stricter than consumers when assessing the finished surface quality. This demonstrates their overestimation of the surface quality required by consumers (H2 validated). Finally, our results showed that denibbing was indispensable on sanded surfaces and on all beech surfaces. It is thus preferable to use cutting conditions that speed up production in these cases. For oak, it was possible to identify a range of planing cutting conditions that generate a finished surface quality acceptable to consumers without the need for a denibbing operation (H3 validated for oak). The issue of raised grain on wood surfaces finished with a waterborne varnish is still far from being fully explained and resolved. In the future, studies of the relationship between the surface reactivity of wood and the occurrence of raised grain will be of considerable interest. This could open up an avenue of research concerning innovative and effective surface treatments to modify the surface reactivity of wood prior to the application of a water-based finish, with the aim of reducing or preventing the occurrence of raised grain whatever the wood species and the machining processes used.

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**Data availability** The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request in the Zenodo repository: Ramanakoto MF, Ramanantoandro T, Eyma F, Castanié B (2018). Data about the visuo-tactile preferences of finished surface quality by French Consumers as regards raised grain on woods. V1. Zenodo. [Dataset]. <https://doi.org/10.5281/zenodo.1318240>

## Compliance with ethical standards

**Conflicts of interest** The authors declare that they have no conflict of interest.

**Statement on ethical approval** The authors declare that they obtained the informed consent from all participants, industrials and all test persons who collaborated for the sensory analysis.

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