

Roughness in sound and vision

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ABSTRACT

In three experiments the perceived roughness of visual and of auditory materials was investigated. In Experiment 1, the roughness of frequency-modulated tones was determined using a paired-comparison paradigm. It was found that using this paradigm similar results in comparison to literature were found. In Experiment 2, the perceived visual roughness of textures drawn from the CURET database was determined. It was found that participants could systematically judge the roughness of the textures. In Experiment 3 the perceived pleasantness for the textures used in Experiment 2 was determined. It was found that two groups of participants could be distinguished. One group found rough textures unpleasant and smooth textures pleasant. The other group found rough textures pleasant and smooth textures unpleasant. Although for the latter groups the relation between relative roughness and perceived pleasantness was less strong.

Keywords: Sensory pleasantness, CURET database, frequency modulated sounds, texture, roughness

1. INTRODUCTION

In product design the visual imagery of a product is one of the aspects that receives the most attention in the conceptual phase of the design. The other senses often receive much less attention and careful consideration. The reason for this is simple; a consumer's initial purchase intent will be based on the visual appearance. This is certainly the case, given the fact that purchases via web-based companies are increasing. Tactile properties of a product may be derived from the visual appearance of that product. If the product has a smooth surface it will probably feel smooth. Sound is sometimes added to webpages to enhance the experience of a product. Therefore, it is interesting to understand how sensory modalities can influence each other. It has been found that manipulating the sound can enhance the feeling of roughness of sand paper¹. The sound was played back through headphones and people reported that the tactile feeling was increased if the sound was made rougher. In our study, we investigated the perceived visual roughness of samples of real world images. In addition, the roughness of a limited set of frequency-modulated tones was investigated using a pair-wise comparison paradigm. Because the roughness of surfaces and sounds leads to a feeling of unpleasantness, this factor can play an important role in the success of products. Furthermore, because roughness is present in different perceptual modalities it is an interesting factor to study in multi-modal research.

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1.1. Auditory Sensory Pleasantness

In auditory perception sensory pleasantness is defined as a function of loudness, roughness, sharpness, and of tonalness (the relation between harmonic related tones and noise).^{2,3} An increase in loudness, roughness, and sharpness results in a decrease in sensory pleasantness, whereas an increase of tonalness will result in an increase in sensory pleasantness. The thresholds for these parameters are well established for certain types of sound. The unit of roughness is asper and is defined as follows: "To define the roughness of 1 asper, we have chosen the 60dB, 1-kHz tone that is 100% modulated in amplitude at a modulation frequency of 70 Hz".³ The roughness for frequency-modulated tones has also been investigated. Two parameters determine the roughness of frequency-modulated tones, the modulation frequency and the deviation frequency. These two parameters also determine the modulation index. An increase of the modulation frequency will result in an increase of the roughness for a certain modulation index until a certain maximum is reached. After this maximum the tone will become less rough when the modulation frequency increases further. An algorithm has been suggested that determines the amount of roughness.⁴ However, in a pilot study we found that this algorithm does not produce the correct value of roughness for the sound of domestic appliances (e.g., shaver) in comparison with subjective ratings. Although the roughness of auditory stimuli has been extensively studied, only a few studies investigated the roughness of visual materials.

1.2. Textures and Visual Roughness

When one looks at surfaces, one often can imagine if a surface will feel rough or smooth. It is, therefore, suggested that the perceived visual roughness of textures is related to the imagined tactile feeling. In other words, if one sees a surface of a material or product, then one imagines how the surface would feel. The relief (surface height function) varies for surfaces of materials. The illumination and viewpoint of a surface will determine the image texture of a surface. In a study, the perceived roughness of noise surfaces has been investigated.⁵ It has been found that a change in two parameters, the magnitude roll-off factor and the RMS height, will affect the perceived roughness of noise surfaces. Since from a product design point of view we are interested in the perception of roughness, in this study we will investigate how people perceive the textures of real world surfaces.

Because there are not that many studies that have investigated the perceived roughness of textures, we have chosen to use images from the CURET database.⁶ The CURET database consists of 60 different real world samples that were each photographed in 200 different combinations of viewing and lighting conditions. The samples can be classified in several categories that include specular surfaces (e.g., artificial grass), diffuse surfaces (e.g., plaster), isotropic surfaces (e.g., cork), anisotropic surfaces (e.g., corduroy), surfaces with large height variations (e.g., pebbles), surfaces with small height variations (e.g., sandpaper), pastel surfaces (e.g., paper), colored surfaces (e.g., carpet), natural surfaces (e.g., moss) and man-made surfaces (e.g., sponge). In Figure 1 four examples of real world textures from the CURET database (from top-to-bottom: pebbles, artificial grass, sponge, cracker) in three different combinations of lighting and viewing conditions are presented. It can be readily seen that, not only the texture differs over the different surface types, but in addition the texture also changes under the different lighting and viewing lighting conditions. For this study, we established that the lighting and viewing condition 122 was the best to investigate the roughness of textures. As mentioned before it has been suggested that people may estimate the roughness of a visual image by imagining its tactile properties. In other words, they use knowledge stored in memory to attribute meaning to the images. In this study, we are interested in the perception of roughness based on the structural properties of the textures, and therefore want to reduce the probability of recognition. Therefore, we converted the images to grey-scale and used a circular region from the samples. In addition, because there is a relation between roughness and pleasantness for the auditory domain, we will investigate if there is a similar relation between roughness and pleasantness in the visual domain.

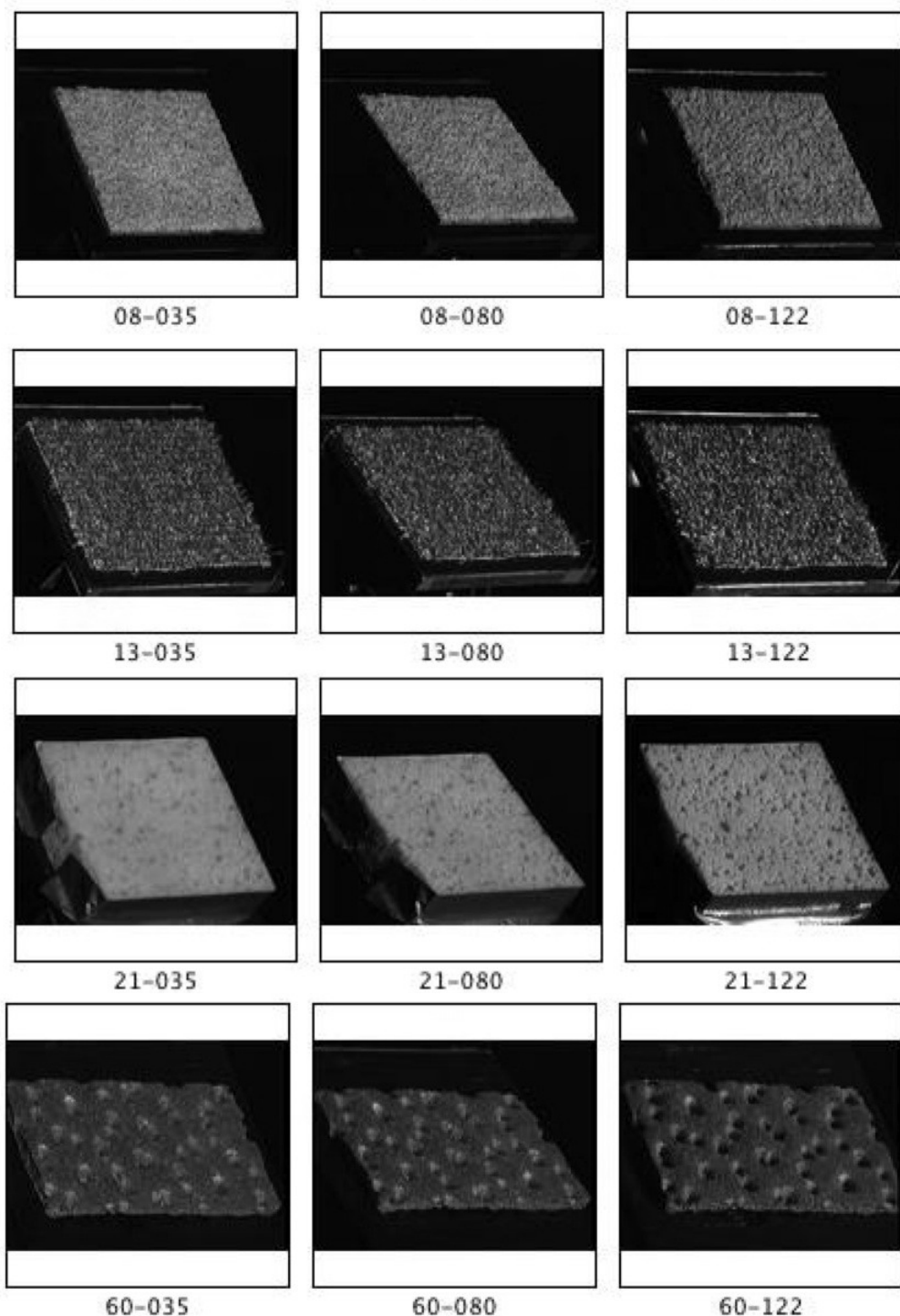


Figure 1. Four samples from the CURET database photographed under three different illuminations and viewing directions and transformed to grey-scale images. From top-to-bottom: pebbles, artificial grass, sponge, cracker. The first number indicates the sample number; the number after the hyphen indicates illumination and viewing direction (for details see: <http://www1.cs.columbia.edu/CAVE/software/curet/html/table.html>).

2. EXPERIMENT 1

The roughness of frequency and amplitude-modulated tones has been studied extensively. In this pilot study, the roughness of frequency-modulated tones will be investigated using a paired comparison task in order to establish if these tones will be usable in future research, in which the interaction between sound and visual materials will be studied. The statistical model to obtain the scale values for the sounds will also be employed to obtain the roughness values for the visual stimuli in Experiment 2; this will allow a better comparison of the perceived roughness between the auditory and visual modalities in future research.

2.1. Method

The amount of roughness was investigated for 15 frequency-modulated tones (varying on 5 levels of modulation frequency and 3 levels of carrier frequency) using a paired comparison paradigm.

2.1.1. Participants

Three subjects (age $M = 21.3$ years) participated in this study. All participants reported normal hearing.

2.1.2. Stimuli

The stimuli were generated using the following formula:

$$sfm(t) = \sin(2\pi f_c t - \frac{\Delta f}{f_{\text{mod}}} * \sin(2\pi f_{\text{mod}} t))$$

Three carrier frequencies (f_c) were chosen: 500 Hz, 1000Hz, and 2000Hz. In addition, five modulation frequencies were chosen (10Hz, 50Hz, 70Hz, 200Hz, 350Hz). The deviation frequency was chosen such that the modulation index ($\Delta f / f_{\text{mod}}$) was 1 in order to avoid a bimodal spectrum that could change the timbre of the tone. Although a modulation frequency above 100 Hz could result in a high difference between harmonic and inharmonic modulations (which may interfere with unpleasantness), we chose to include these frequencies to explore the effect on roughness. The sounds were normalized in intensity.

2.1.3. Apparatus

The experiment was performed in a soundproof booth. The stimuli were presented using a specially written program in QT (object C variant). The program was self-paced and ran on a Macintosh G4 computer. The sounds were presented through a Sennheiser headphone at a comfortable listening level.

2.1.4. Procedure

A participant received written instructions concerning the procedure of the experiment. It was explained that two sounds were played sequentially, after which a judgment had to be made about which of the two sounds was the roughest. After a participant was seated in front of the computer screen, (s)he could press a button to start the experiment. A button was activated on the screen, which a participant could press to listen to the first sound. After the first sound was heard, the button was deactivated and the button that had to be pressed to listen to the second sound was activated. After the two sounds were heard, the participant could press a radio-button to indicate which sound was the roughest. Only after the two sounds were heard and the choice was made could the participant continue to the next trial. The 15 stimuli resulted in 210 pairs to be judged (each sound was presented as the first and second sound). The order of the sound pairs was randomized over different participants. A participant was instructed to take a small break after listening to 50 pairs.

2.2. Results & Discussion

The data from the paired comparison task were analyzed using the Bradley-Terry-Luce (BTL) model.^{7,8} The model converted the preference choices on the pairs into coefficients (scale values) for each stimulus. The model requires that one of the coefficients (scale values) is set to zero; all other coefficients are then determined relative to this zero coefficient. In Figure 2 the relative roughness as a function of modulation frequency (10Hz, 50Hz, 70Hz, 200Hz, 350Hz)

and carrier frequency (500Hz, 1000Hz, and 2000Hz) is shown. It can be seen that the curve is an inverted u-shape (which is consistent with the findings of earlier research). In general, roughness increases if the carrier frequency increases. In addition, roughness increases for modulation frequencies from 10Hz through 70Hz, and decreases again for modulation frequencies higher than 70Hz. It is interesting to note that for the carrier frequencies of 500Hz and 1000Hz, roughness is the same for modulation frequencies of 200Hz and 350 Hz. Note that the increase in roughness for the carrier frequency of 200Hz may be confounded with an increase in sharpness. In general, it can be concluded that the results resemble earlier findings in literature even when using only three subjects. It is thus confirmed that we could successfully employ this paradigm in future research to establish the roughness of frequency-modulated tones. In addition, the figure also shows that tones can be chosen until a maximum modulation-frequency of 70Hz with that avoiding the increase in difference between harmonic and inharmonic modulations for modulation-frequencies higher than 100Hz (which may interfere with unpleasantness).

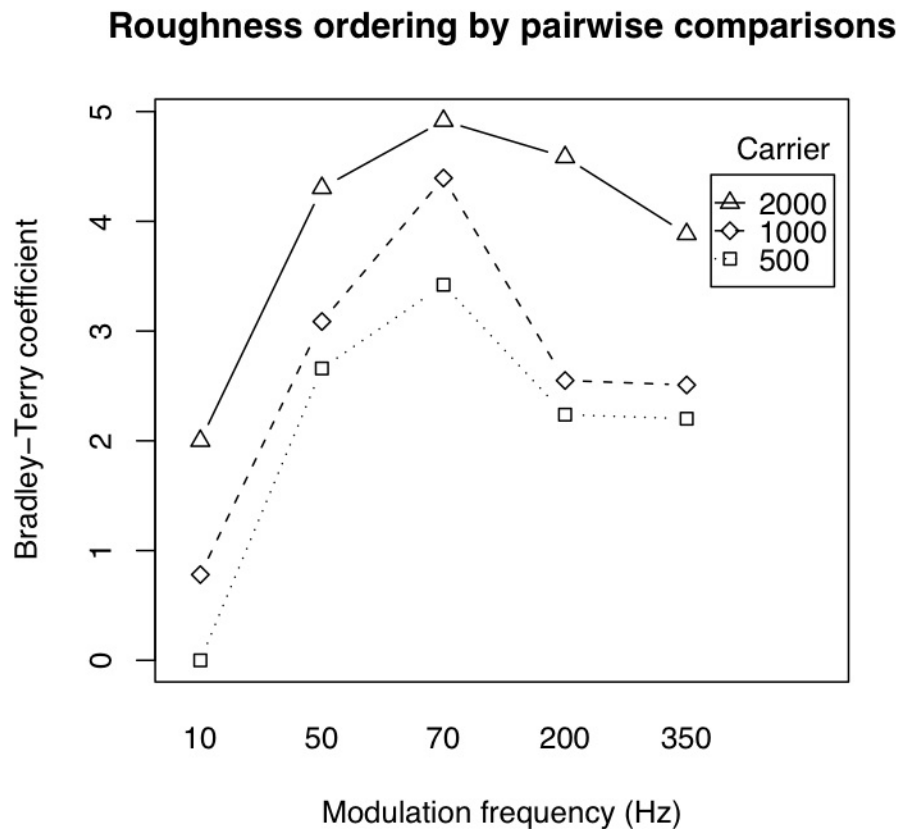


Figure 2. Relative roughness in scale values (BTL-model) as a function of modulation frequency (x-axis) and carrier frequency (legend).

3. EXPERIMENT 2

As mentioned before, the perceived roughness of textures often plays an important role in product user interaction. It may determine if one is willing to touch (by feet or hand) an object or if one needs to do this very carefully. Unfortunately not much is known concerning the perception of roughness in visual textures. Therefore, the real world surfaces from the CUREt database were used to obtain a wide range of textures.

3.1. Method

The (relative) roughness of 49 circular regions of photographs of surfaces from the CURET database was determined. The roughness of the pictures was judged in a paired comparison task.

3.1.1. Participants

Forty-eight participants volunteered in this experiment. The participants were employees or students from the Delft University of Technology (age $M=26.3$ years). All participants had normal or corrected vision.

3.1.2. Stimuli

Forty-nine out of the sixty textures from the CURET data in one out of the 200 different combinations of viewing and lighting conditions were selected by visual experts (lighting and viewing condition 122). According to these experts, the textures in this specific viewing and lighting condition were best visible. In this condition, the polar angle of the viewing direction was .88, the azimuthal angle of the viewing direction was -2.38, the polar angle of the illumination direction was .88, and the azimuthal angle of the illumination direction was -.76. The 12 samples that were not used were 7, 9, 23, 25, 29, 30, 31, 32, 34, 37, 55, and 57. These samples were too similar to other samples (no distinction possible) or the source of the sample was too easy to recognize. As mentioned before, it is important that the samples not be recognized in order to have the judgment relate to the visual features of roughness. Therefore, a circular region was selected. In Figure 3, four examples of circular regions of the samples of Figure 1 can be seen in lighting and viewing condition 122 (from left to right 8, 13, 21, and 60. The picture size was 288x288 pixels.

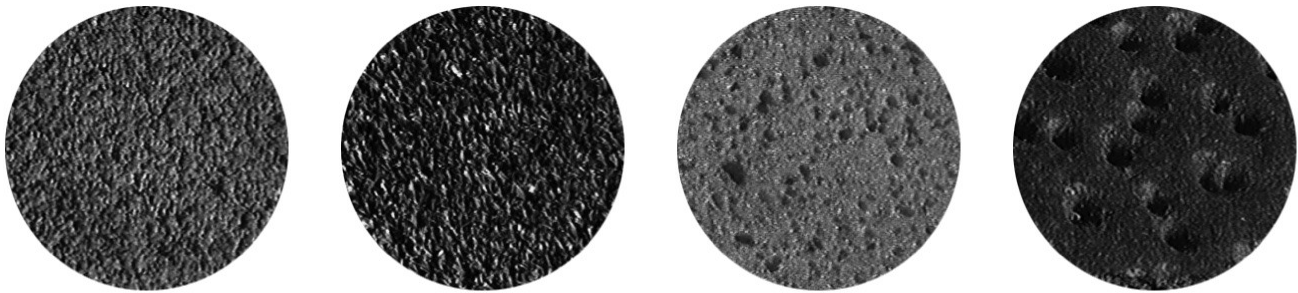


Figure 3. Examples of the circular regions of samples of the CURET database. The pictures are regions of the samples in Figure 1 with lighting and viewing condition 122. The samples are from left to right 8, 13, 21, and 60.

3.1.3. Apparatus

The stimuli were presented using a special program written in MAX/MSP. A specially designed external button box was used to collect the responses. The program ran on a PowerMac G4 733MHz computer with a NVideo Geforce card. The monitor employed was a LaCie Electron 22 blue display, set at a resolution of 1024x768 and a 75Hz refresh rate. The contrast and brightness levels were set at 100%. The monitor was calibrated. A chin-rest was used to have a fixed distance between a participant and the monitor (65 cm). This resulted in a visual angle of 8.88 degrees. The distance between the stimuli within a pair was 4.0 degrees visual angle.

3.1.4. Procedure

A participant received written instruction about the procedure of the experiment. A participant was requested to put his chin on a chin-rest in order to have a fixed position from the monitor. A pairwise comparison paradigm was employed in which a participant had to judge which picture was rougher (binary choice). Forty-nine stimuli result in 1176 pairs. Since this number is too high for one participant to judge, 180 pairs were randomly selected for each participant. All the pairs would then be rated over the group of participants. The order of the pairs and the order of the stimuli within a pair

was randomized. A fixation cross preceded each experimental trial. The 180 trials were divided in 6 blocks. After each block, a participant could take a small break and the experiment continued after pressing a button. Two external buttons were used, by which a participant could choose the left or right picture. The duration of presentation for each pair was approximately 700 ms. A training trial of 2 pairs preceded the experiment in order to familiarize the subject with the procedure.

3.2. Results & Discussion

The data were aggregated over the subjects. Thus, for the stimuli in each pair a frequency count was obtained that reflected the choice that one stimulus was rougher than the other. The pairwise data were analyzed with the Bradley-Terry-Luce (BTL) model. This model yielded scale values for each stimulus. The scale values as a function of CURET texture number can be seen in Table 1. A scale value can be interpreted as a relative measure for roughness. A negative number indicates that the texture is rough. The highest value for roughness is -8.14 for CURET texture 47 and the lowest value for roughness (smoothness) is 2.30. In addition, it can be observed that for the middle values the textures are more clustered (there are small differences between the scale values of consecutive stimuli, whereas for the very rough and very smooth textures the differentiation is much larger between consecutive textures).

Table 1. Scale Values (BTL) as a Function of CURET Picture Number. The Pictures are ordered by their Scale Value. A Negative Number indicates Rough, A Positive Number indicates not Rough.

<i>CURET#</i>	<i>Scale Value</i>	<i>CURET#</i>	<i>Scale Value</i>	<i>CURET#</i>	<i>Scale Value</i>
47	-8.14	19	-4.63	51	-1.36
45	-7.23	60	-4.45	56	-1.36
53	-7.17	4	-4.27	44	-1.29
13	-6.56	14	-4.15	20	-1.13
35	-6.17	27	-4.11	2	-0.97
28	-6.12	54	-4.08	41	-0.86
15	-6.03	43	-3.87	6	-0.43
61	-5.98	26	-3.60	33	-0.42
58	-5.95	24	-3.48	46	-0.07
11	-5.69	21	-3.39	1	0.00
50	-5.55	16	-3.17	22	0.29
8	-5.36	49	-3.02	42	0.47
48	-5.05	3	-3.01	5	1.97
10	-5.00	38	-2.52	12	2.05
59	-4.92	52	-2.34	17	2.30
40	-4.83	36	-2.19		
18	-4.81	39	-2.16		

In Figure 4 the CURET textures are depicted. The textures are ordered on the basis of the scale values of Table 1. Relative roughness increases from top to bottom and from left to right. Thus, the texture depicted at the top-left is number 47 and the picture depicted at the bottom-right is number 17. It can be readily seen that the roughness judgments appear to be systematic. Note that only the order is presented not the actual distance between the scale values.

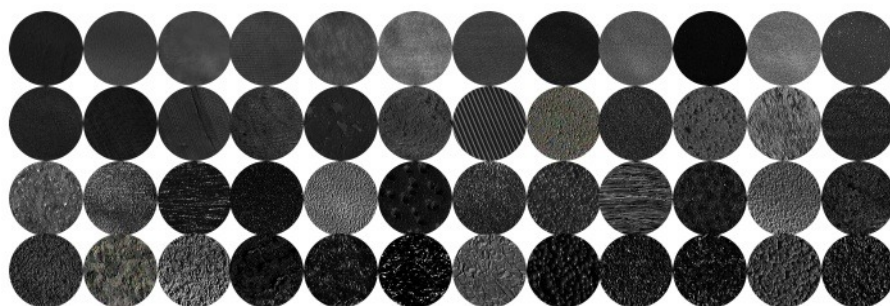


Figure 4. CURET textures ordered on the basis of the scale values from the BTL-model. Roughness increases from top to bottom and from left to right.

The main finding of this experiment is that people can systematically determine the roughness of textures. It was also found that people could not recognize the actual source of the texture. Thus, this indicates that roughness judgments were probably based on the perceived structure of the textures and not on the basis of the interpretation of the type of the source. For example, artificial grass (CURET# 13) has a scale value of -6.56. It is likely that if one knew that this is grass then one would have considered it as less rough because grass is soft. A similar top-down effect of meaning attribution has been suggested for sounds.⁹

4. EXPERIMENT 3

In Experiment 2, the relative roughness for the CURET textures was determined. In the model for auditory sensory pleasantness the factor roughness is one of the four factors that determines the level of pleasantness. An increase in roughness will result in a decrease of pleasantness. In the next experiment, we investigated if there is an analogous relation between roughness and pleasantness in the visual domain. Although it is known that pleasure can be determined for pictures (photographs) of real world situations,¹⁰ it is not known if the level of pleasure can be systematically determined for abstract textures. In this experiment, the pleasantness of CURET textures was determined. In addition, we investigated whether there is a systematic relation between roughness and pleasantness for the CURET textures.

4.1. Method

The level of pleasantness for 45 CURET textures was determined on an 8-point scale.

4.1.1. Participants

Twenty-four participants (age $M=19.6$) volunteered in this experiment. All were students from the Delft University of Technology and had normal or corrected vision.

4.1.2. Stimuli

The same CURET textures of Experiment 1 were used. After analyzing the data of Experiment 2 (including cluster analysis on the scale values) four outliers were removed. These were textures: 12, 35, 38, and 60. The source for these textures was too easy to determine.

4.1.3. Apparatus

The stimuli were presented using a special program written in Mac-QT. The program ran on a PowerMac G4 733MHz computer with a Video Geforce. The monitor employed was a LaCie Electron 22 blue display, set at a resolution of 1024x768 and a 75Hz refresh rate.

4.1.4. Procedure

A participant received written instructions concerning the procedure of the experiment. The participant was instructed to rate visual images on a scale from 1 to 8, with 1 being very unpleasant and 8 being very pleasant. After the participant was seated in front of the computer screen, (s)he could start the experiment by pressing the return button or click the button on the screen with a mouse. Next to the picture, 8 radio buttons were present that reflected the eight values of pleasantness. Only if a subject pressed one of the 8 radio buttons could the subject continue to the next trial. The order of the trials was randomized. The experiment was self-paced. After a participant rated the 45 stimuli, (s)he was thanked for their participation and asked on what basis the choice was made. A training trial preceded the actual experiment with 4 pictures from the IAPS database.

4.2. Results

The mean and the standard deviation of the rating values were determined. It was found that participants showed differences in using the scale. Not all participants used the entire range of the scale. Therefore, it was decided to convert the rating values to z-scores for each individual. In Figure 5, the CURET textures have been depicted in order of decreasing pleasantness from top-to-bottom and from left-to-right. Only the order is presented and not the distances between the textures on the basis of their difference in rating values. Comparing Figure 5 with Figure 4 it appears that the order of the textures for pleasantness deviates from the order obtained from the roughness judgments. In addition, it can also be seen in Figure 5 that rough textures appear to be mixed up with smooth textures. The data were then reanalyzed by inspecting the individual ratings for each texture graphically. It was found that certain subjects rated textures with low scale values (rough texture) as being pleasant, whereas other subjects rated the same (rough) texture as unpleasant. A hierarchical cluster analysis using Wards-method was conducted on the z-scores over textures. It was found that two groups of participants could be distinguished. Participants in one group rated certain textures as pleasant, whereas participants in the other group rated the same pictures as unpleasant and visa versa.

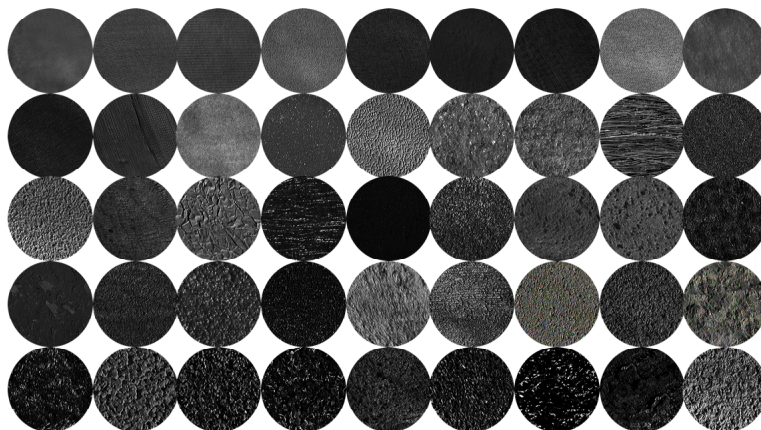


Figure 5. Ordered CURET textures on the basis of the overall pleasantness rating.

In Table 2 the mean pleasantness ratings in z-scores are presented as a function of CURET number. The stimuli are ordered on the basis of the Scale values obtained in Experiment 2. Two groups were determined on the basis of the cluster analysis a smooth-unpleasant group ($n=10$) and a rough-unpleasant group ($n=14$). The rough-unpleasant group rated the rough pictures as unpleasant, whereas the smooth-unpleasant group rated the rough pictures as pleasant. It can be seen that for textures with scale values in the middle regions the pleasantness ratings between the groups are relatively similar.

Table 2. The Mean Z-scores as a function of CURET number.

Pleasantness			Pleasantness		
CURET#	Rough Group	Smooth Group	CURET#	Rough Group	Smooth Group
47	-0.69	0.84	24	-0.51	-0.49
45	-0.58	0.20	21	-0.25	-0.90
53	-0.76	0.58	16	0.03	-0.79
13	-0.83	0.35	49	-0.57	-0.44
28	-0.08	1.29	3	0.13	-0.62
15	-0.85	0.78	52	-0.08	-0.60
61	-0.54	0.77	36	-0.36	-0.09
58	-0.98	0.41	39	-0.10	-0.30
11	-0.76	0.10	51	0.68	-0.18
50	-0.56	-0.10	56	0.84	0.85
8	-0.50	-0.61	44	0.93	0.56
48	-0.85	-0.28	20	0.35	-0.42
10	-0.09	-0.07	2	0.73	0.00
59	-0.23	-0.21	41	-0.12	-0.44
40	0.08	1.10	6	1.02	-0.47
18	-0.33	-0.41	33	0.75	0.16
19	-0.08	-0.35	46	1.08	0.23
4	0.34	0.95	1	0.71	-0.70
14	-0.40	-0.71	22	0.75	-0.55
27	-0.08	1.23	42	0.87	-0.03
54	-0.38	-0.33	5	1.45	0.34
43	0.25	0.18	17	0.94	0.03
26	-0.40	-0.85			

In Figure 6 the mean pleasantness score (z-value) as a function of relative roughness (scale value BTL) and group is presented. The circles and crosses represent the textures from the CURET database. Note that because the data are divided into two participants groups, each CURET texture is presented twice. Roughness decreases from left (negative values) to right (positive values). It can be seen that for the group indicated by open circles, pleasantness increases with an increase of roughness, whereas for the group indicated by the crosses pleasantness decreases with an increase of roughness. It can also be seen in the figure that for the group indicated by the crosses the relation between pleasantness and roughness is stronger than for the groups indicated with the circles. The correlation between the scale values and pleasantness for the *rough-unpleasant* group is .86. The correlation between the scale values and pleasantness for the *smooth-unpleasant* group is .30. Thus, confirming the aforementioned stronger relationship between roughness and pleasantness for the rough-unpleasant group.

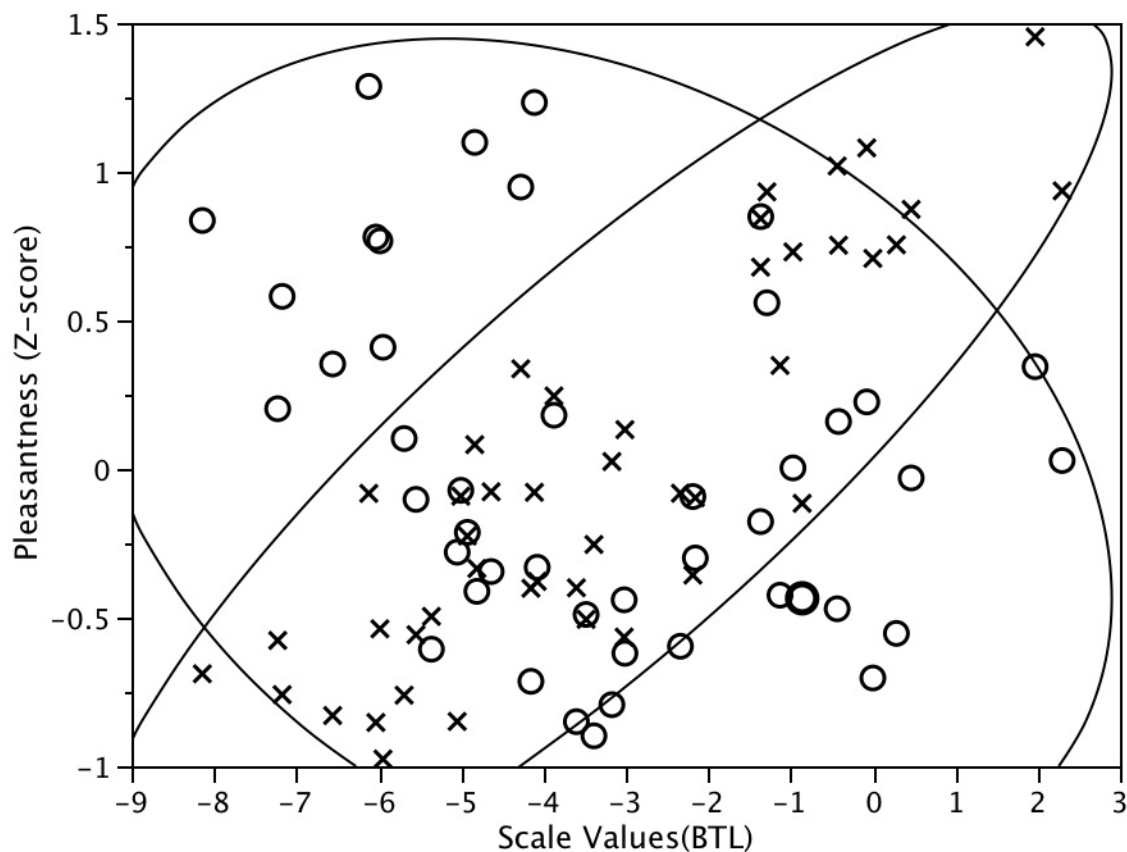


Figure 6. Pleasantness ratings as a function of scale value and participant group. Open circles indicate the group that rated rough pictures as pleasant and smooth pictures as unpleasant. Crosses indicate the group that rated rough pictures as unpleasant and smooth pictures as pleasant. Density ellipses of $P=0.95$.

5. Discussion

Our main finding is that roughness for auditory and visual stimuli can be systematically determined using a paired comparison paradigm. The stimuli in both domains show a good differentiation between stimuli with different textures and between frequency-modulated sounds generated by using different modulation frequencies and modulation depth. The finding for the frequency-modulated sounds is similar to earlier findings reported in literature that employed different experimental paradigms. It was suggested that in future studies the modulation frequency should be below 100Hz. For the textures derived from the CURET database people were systematically capable of determining the roughness. In addition, it was found that roughness is not in one-way related to the perceived pleasantness. This differs from the reported systematic relation between roughness and pleasantness in the auditory domain. Two groups of subjects could be distinguished. One group finds rough textures pleasant, whereas the other group finds smooth textures more pleasant. The reason for this finding is unknown. Because the relation between roughness and pleasantness for the smooth-unpleasant group is less strong, it may be suggested that this group is less sure about their judgment. Furthermore, different subjects participated in the two experiments. Therefore, a relation between roughness and pleasantness could only be made over the aggregated data. In future studies we intend to have the same subject judge pleasantness and roughness. Another aspect is the employed paradigm. A pairwise comparison paradigm was employed for the roughness judgments, whereas a rating scale was used to obtain the pleasantness data. In future studies we intend

to derive objective measures from these textures of generate synthetic textures in order to find the determinant factors that underlie the perceived roughness. In addition, we intend to use the same experimental paradigm to obtain values for roughness and pleasantness. Furthermore, we want to investigate how auditory and visual stimuli can influence each other if they are varied on the same perceptual dimension (e.g., roughness).

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