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RESEARCH ARTICLE

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Audiotactile interactions in roughness perception

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Abstract The sounds produced when we touch textured surfaces frequently provide information regarding the structure of those surfaces. It has recently been demonstrated that the perception of the texture of the hands can be modified simply by manipulating the frequency content of such touch-related sounds. We investigated whether similar auditory manipulations change people's perception of the roughness of abrasive surfaces (experiment 1). Participants were required to make speeded, forced-choice discrimination responses regarding the roughness of a series of abrasive samples which they touched briefly. Analysis of discrimination errors verified that tactile roughness perception was modulated by the frequency content of the auditory feedback. Specifically, attenuating high frequencies led to a bias towards an increased perception of tactile smoothness. In experiment 2, we replicated the rubbing-hands manipulation of previous experimenters while participants rated either the perceived roughness or wetness of their hands. The wetness scale data replicated the results in the literature, while the roughness scale data replicated the result from experiment 1. A final experiment showed that delaying the auditory feedback from the hand-rubbing reduced the magnitude of this parchment-skin illusion. These experiments demonstrate the dramatic effect that auditory frequency manipulations can have on the perceived tactile roughness and moistness of surfaces, and are consistent with the proposal that different auditory perceptual dimensions may have varying salience for different surfaces.

Keywords Multisensory · Texture · Touch · Hearing · Human

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Introduction

Our perception of the world around us is inherently multisensory; that is, we normally assess the objects we encounter via several senses simultaneously (Driver and Spence 2000; Stein and Meredith 1993). For example, an apple's ripeness is judged initially by its colour and smell. However, gustatory, tactile and auditory cues also contribute to our perception once we bite into the fruit. In fact, auditory cues frequently occur when we touch or interact with objects, and these sounds often convey potentially useful information regarding the nature of the objects with which we are interacting (cf. Gaver 1993a, 1993b). Research has shown that, when these auditory cues are presented in isolation, they can provide sufficient information for people to assess the size of objects and even what material they are made from (Freed 1990; Katz 1925; Warren and Verbrugge 1984; Wildes and Richards 1988). Extending these findings to a more applied domain, researchers have even shown that people's perception of the quality of a car is influenced not only by the sound of its engine, but also by more subtle auditory cues such as the sound made when the car door is closed (Keiper 1999; Miśkiewicz and Letowski 1999; Packard 1957, p. 111). As well as quality, sound can denote 'character' and become strongly associated with particular products. One example is that Harley-Davidson went to great lengths to try to patent the distinctive sound of their motorcycle engines, which they consider to be an essential part of the experience of ownership (Sapherstein 1998). Results such as these demonstrate that auditory cues contribute to multisensory perception during everyday interactions with objects.

One aspect of multisensory perception that has received considerable interest is the perception of textured surfaces (see Lederman 1982 for a review). Lederman noted that 'perceiving the texture of a surface by touch is a multisensory task in which information from several different sensory channels is available. In addition to cutaneous and thermal input, kinesthetic, auditory, and visual cues may be used when texture is perceived by touching a surface' (Lederman 1982, p. 131; see also Taylor et al. 1973). Given that we naturally assess the texture of many surfaces by stroking them with the fingertips (Drucker 1988), one might expect that touch-related sounds would be particularly prominent in modulating our perception of tactile texture.

Laboratory-based research suggests that people can indeed discriminate touch-produced sounds from different surfaces (e.g. abrasive papers), when they are presented in isolation (Lederman 1979; experiment 1). However, in subsequent experiments, Lederman (1979; experiments 2–3) found that tactile texture cues completely dominated auditory cues in determining texture perception when *congruent* information was presented to both modalities simultaneously. Similarly, Heller (1982) has found that the availability of auditory input did not improve the discrimination of abrasive surfaces compared with that seen using tactile and visual modalities alone. Again, it seems that audition was subservient to the tactile (and visual) modalities. It is possible that this bias towards tactile information may have an attentional basis, in that people simply choose to direct their attention towards the more informative tactile modality when both sources of information are available (Posner et al. 1976; Spence et al. 2001; Welch and Warren 1980). Alternatively, the very act of touching a textured surface may actually result in attention being reflexively directed towards touch. Finally, it is also possible that the bias towards tactile information has an ecological basis in that low-level sound cues are frequently masked by the general background noise in many everyday situations, thus potentially rendering touch more informative on a day-to-day basis (cf. Lederman 1979).

However, Jousmäki and Hari (1998) have recently reported that auditory cues can influence tactile judgements under certain conditions. They showed that perception of the palmar surface of the hands is modulated by the presentation of modified sounds. Participants in their experiment were required to rub their hands together while rating the feel of the palmar skin of their hands along a 'rough/moist-smooth/dry' composite scale. The sound of the hands being rubbed together was presented to the participants over headphones, via a microphone placed near the participant's hands. Jousmäki and Hari reported that participants judged the skin of their hands to feel 'smoother/drier' when either the overall sound level was increased, or if just sounds within the 2- to 20-kHz frequency range were amplified, an effect they labelled the 'parchment-skin illusion'. Participants also judged their hands to feel 'rougher/moister' when sounds in this frequency range were attenuated.

The results of Jousmäki and Hari's (1998) seminal study provide intriguing evidence regarding the influence of nonveridical auditory feedback on tactile perception (see also von Schiller 1932, for an early demonstration of the effect of sound on tactile roughness perception). However, it should be noted that Jousmäki and Hari's experimental protocol suffers from several interpretational limitations, perhaps the most important of which are related to possible experimenter-expectancy effects and task demands (Choe et al. 1975; Intons-Peterson 1983; Orne 1962; Rosenthal 1967). Specifically, participants were presumably aware that their palmar skin surface did not actually change during the course of their participation in Jousmäki and Hari's experiment. Hence, it could be argued that some component of the behavioural effects reported may simply reflect task demands associated with the experimental situation, rather than genuine perceptual effects resulting from multisensory integration. That is, participants may have responded in the way in which they *thought* the experimenter wanted them to respond, rather than because their hands genuinely *felt* different (cf. Intons-Peterson 1983; Orne 1962).

Informal testing of nearly 1,000 people by the authors at the Royal Society Summer Science Exhibition (July 2001) confirmed the impression that the parchment skin illusion does occur in many people. However, the fact remains that the results of Jousmäki and Hari's (1998) study reflect some unknown combination of genuine perceptual effects and task demands. Hence, as for many other illusions, such as the ventriloquism illusion (Howard and Templeton 1966) or the rubber hand illusion (Botvinick and Cohen 1998), researchers must develop more robust and objective measures of the phenomenon under investigation to convince the skeptical observer of the genuinely *perceptual* nature of such effects (Bertelson and Ascherleben 1998; Caclin et al. 2002; Pavani et al. 2000; Recanzone 1998).[1]

A further limitation regarding the interpretation of Jousmäki and Hari's (1998) study is that only some of those participants who experienced the illusion in preliminary testing took part in the main experimental investigation (11 of 17 participants). It is therefore uncertain how common the parchment-skin illusion is across the general population and whether the effect is sufficiently strong to reach statistical significance when tested in a randomly selected group of participants.

Finally, Jousmäki and Hari's (1998) use of a composite response scale means that it is unclear whether their auditory manipulations resulted in a change in the perceived roughness of the participant's hands, a change in the perceived moistness of their hands, or changes in both dimensions simultaneously. If the frequency manipulation affects the perceived moistness of the hands without affecting their perceived roughness, Jousmäki and Hari's results are consistent with those of Lederman (1979), who reported that auditory cues have no effect on tactile roughness perception. So although Jousmäki and

[1] Jousmäki and Hari (1998) have argued that the fact that the parchment-skin illusion is reduced by the introduction of auditory delay (by more than 100 ms) demonstrates the truly perceptual nature of their effect. However, it should be noted that the effect of asynchrony was tested in only two participants, and moreover no estimates of the size of this decrement in the effect attributable to the introduction of the asynchrony are given in their brief correspondence. See our experiment 3 for a more detailed investigation into the effects of asynchrony on the parchment-skin illusion.

Hari's study provides an innovative and informative preliminary investigation into the effect of modified auditory cues on tactile perception, it is clear that further investigation is required to clarify the underlying nature of their effect.

In the present study, we investigated whether a parchment-skin illusion could be demonstrated under more rigorous psychophysical testing conditions. We used established tactile materials – abrasive papers – for which a wealth of psychophysical data already exists (Lederman 1982), and a speeded, forced-choice discrimination task for which extensive psychophysical data also exists (Pavani et al. 2000). In such tasks, interaction between sensory modalities can be indicated by changes in response times and/or discrimination accuracy (Klein 1977; Spence et al. 2001). Given that participants could not see the samples they were classifying, nor did they know how many samples (or manipulations) there were, our experimental design also minimized any effect of task demands (or subjective bias) on performance.

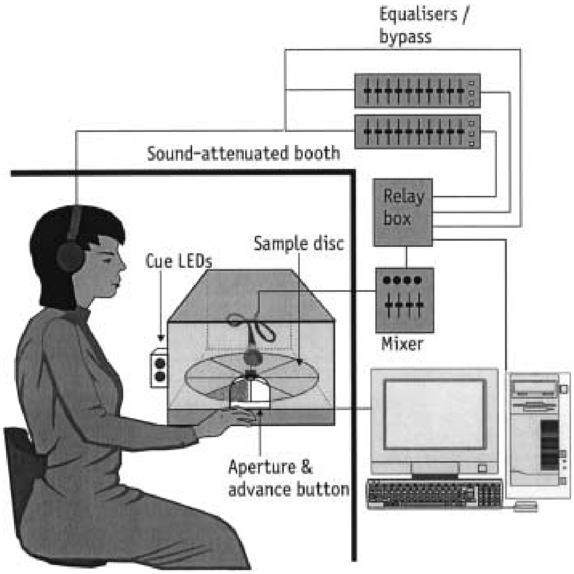


Fig. 1 Experimental equipment. The presentation device is shown in transparent view. Note that during the experiment the participant sat directly in front of the test equipment; she is shown displaced to the side here to assist clarity. The aperture for the hand was covered by a cloth flap, which hid the sample disc from view during the experiment. Again, for reasons of clarity, this is not shown

Experiment 1

Materials and methods

Participants

Fifteen subjects participated in experiment 1 (6 men and 9 women, with ages ranging from 22 to 31 years). All were naïve as to the purpose of the experiment and all gave their informed consent prior to their inclusion in the study. The experiments reported here were approved by the Ethics Committee at the Department of Experimental Psychology, Oxford University, and were performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Apparatus

Two abrasive paper samples were used, 400- and 800-grade, closed-coat silicon carbide papers. These were chosen (via pilot studies) such that the expected performance was approximately 80% correct when discriminating whether the rough or smooth paper was touched in a single-interval, unspeeded, sound-attenuated task (participants wore sound-attentuating earplugs, which reduced the noise by approximately 25 dB; part 03048; Seaton, UK).

Stimuli were arranged on a 31-cm-diameter circular plastic disc, within 45° segments (see Fig. 1). The disc was mounted on a motorized platter, using Velcro fasteners. The drive for the disc was provided by a stepper motor which required 2,000 steps for one complete rotation. The equipment was located inside a wooden box, which contained an aperture through which the participant could insert their preferred hand to touch the samples. This aperture was masked by a cloth flap, which prevented participants from viewing the sample under test. A response key located directly above the aperture and within the box itself was used by participants to advance the trials manually. The experiment was conducted in a sound-attenuated booth.

A Rode NT1 condenser microphone powered by a Spirit Folio Notepad mixer was located 10 cm directly above the centre of the test sample. The output from the mixer was fed through a computer-controlled relay switching box which redirected the output through either one of 2 one-third-octave graphic equalizers (Phonic; model PEQ3300), or else via cables bypassing these devices. Sounds were subsequently fed back to the participant via the headphone socket of the mixer to a pair of Beyerdynamic DT531 headphones. The amplification level was set at approximately 55 dB, for the unmodified touch sound condition. This level corresponds to the level naturally available at (or very near) the fingertip.

Design

A single-interval, speeded, forced-choice procedure without error feedback was used. The participants' task was to state whether the stimulus presented was the rough or smooth sample. This choice was made by briefly releasing one of two foot-switches.

The design was a fully crossed Frequency manipulation (attenuated, veridical, or amplified) × Sample roughness (rough versus smooth) × Experimental block (4) factorial. Each of the sound conditions were experienced within each session-block of 96 randomised trials (32 trials per sound condition). The experimental blocks were run consecutively, with a short break between each block.

In the veridical sound condition, the sounds made when participants touched the abrasive samples were fed back without frequency adjustment. In the amplified sound condition, the touch-produced frequencies in the range 2–20 kHz were increased in amplitude by 12 dB, according to the one-third-octave resolution of the graphic equalizer. In the attenuated sound condition, sounds within this frequency range were reduced in amplitude by 12 dB. Response times and errors rates were recorded.

Procedure

Participants were informed that they would be repeatedly categorizing one of a pair of sandpapers as either the rough or smooth member of the pair. The touching action suggested was to use the first finger of the preferred hand, touching along a vector away from the centre of the wheel. This would lead to the finger traversing about 4 cm of stimulus surface. Participants were specifically instructed to ignore the touch sounds they heard, and to base their judgements exclusively on the feel of the touched surface.

Instructions and cues during the experimental session were presented to participants via colour-coded LEDs mounted on the side of the wheel box. A green LED cued the participant to touch the sample, and a red LED indicated that the participant should press the advance button and keep their hand clear of the rotating wheel surface. On pressing the button, the wheel rotated to the next test sample. On cue, the participant then touched this sample and had 4,000 ms in which to make a speeded discrimination response. This cycle of button-press and response continued until the end of an experimental block (approximately 5 min), after which the participant took a short break.

Two initial practice blocks of 20 trials each were used to train the participant on the discrimination task. During these trials, only veridical sounds were experienced and error feedback was given. Data were discarded from these blocks. The subsequent 4 (experimental) blocks, each of 96 trials, included all sound conditions without feedback, and provided the data for the subsequent analysis. The entire experimental session, consisting of 2 practice blocks and 4 experimental blocks, took just over 30 min to complete.

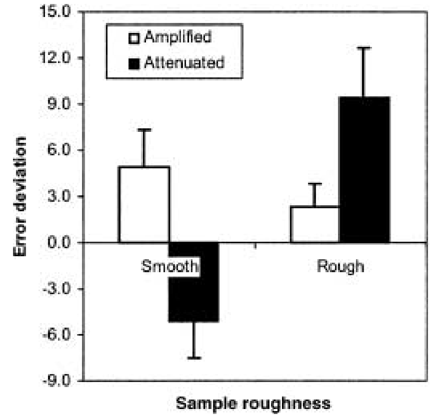


Fig. 2 Error deviations (defined as test condition error rate minus normal sound error rate) for both sound manipulations (high-frequency amplified and high-frequency attenuated sound) and both sample roughness levels (rough and smooth). *Error bars* show ±1 SE

Stimulus samples were changed regularly, typically after a participant had completed a session. In this case, each sample would have been touched 232 times. Although this was a relatively large number of touch trials for the stimuli, the brief nature of the tactile contact during each trial ensured that the stimuli were not excessively worn by the end of a session.

Results

The data from experiment 1 are presented in Table 1 and Fig. 2. For the error data, the error proportions in the normal sound condition were subtracted from the error

Table 1 Performance in the abrasive discrimination task of experiment 1 as a function of sound manipulation and sample roughness. Means and standard errors are shown for response times (milliseconds) and error percentages

		Sound manipulation						Mean by sample roughness
		Veridical		Amplified		Attenuated		
		Mean	SE	Mean	SE	Mean	SE	
Response times								
Sample roughness	Rough	946	38.7	940	35.5	944	32.6	944
	Smooth	914	35.4	916	40.5	875	33.6	902
Mean by sound manipulation		930		928		910		
Error proportions								
Sample roughness	Rough	12.3	1.8	14.7	2.7	21.7	3.7	16.3
	Smooth	13.4	2.9	18.2	4.4	8.2	1.6	13.3
Mean by sound manipulation		12.8		16.5		15.0		

proportion in each of the sound manipulation conditions for each participant. This was carried out separately for rough and smooth sample roughness levels, to give error deviations which treat the baseline, normal sound condition as a control. (Baseline error rates for the veridical sound condition were 12.3% for classification of rough samples and 13.4% for classification of smooth samples; see Table 1). These data were then analysed by a Sample roughness (rough versus smooth) × Frequency manipulation (amplified versus attenuated) repeated-measures analysis of variance (ANOVA). For analyses reported in this report, all post hoc comparisons used Bonferroni-corrected *t*-tests (where $P<0.05$ prior to correction).

There was a statistically significant main effect of Sample roughness upon error deviations ($F_{1,14}=7.19$, $P=0.018$) and a significant Sample roughness × Frequency manipulation interaction ($F_{1,14}=5.67$, $P=0.032$). There was no overall effect of Frequency manipulation ($F_{1,14}=1.27$, $P=0.279$, n.s.). The main effect of roughness indicated that more errors were made overall for the rough (mean 5.9% errors above baseline) than for the smooth samples (0.1% below baseline). Overall, rough samples with either sound manipulation (i.e. high-frequency attenuation or high-frequency amplification) led to more errors than for rough samples in the veridical sound condition; the 95% confidence interval around the mean error deviation (9.8, 1.9) did not include zero for the rough sample data.

The significant interaction, shown in Fig. 2, shows that the frequency manipulations altered participants' responses in a manner consistent with a change in their perception of tactile roughness. In particular, for the smooth sample, amplifying the high-frequency sounds led to a significant increase in errors as compared to attenuating these frequencies. No other pairwise comparisons showed significant differences, although for the rough sample a trend is evident whereby amplifying the high frequencies led to fewer errors than attenuating the high frequencies. These results are consistent with the high-frequency boost resulting in an increased perception of roughness (resulting in significantly more errors for the high-frequency amplified smooth sample and a trend of less errors for the high-frequency amplified rough sample), while the high-frequency attenuation led to an increased perception of smoothness (with the reverse pattern of results).

In addition to error rates, median response times (RTs) were also calculated for all Sample roughness × Frequency manipulation conditions. There were no statistically significant effects of Sample roughness or Sound manipulation on RTs as analysed by a repeated-measures ANOVA. However, the main effect of sample was borderline significant ($F_{1,14}=4.58$, $P=0.051$), consistent with a trend towards faster classification responses for smooth stimuli than for rough stimuli (902 versus 944 ms).

Discussion

The significant bias in tactile roughness judgements induced by the sound manipulations used in experiment 1 confirms Jousmäki and Hari's (1998) central claim that sound can modulate touch. In particular, we found that the attenuation of high-frequency sounds altered discriminative performance consistent with the production of a smoother tactile sensation, whereas high-frequency amplification led to a trend towards rougher sensations. Moreover, our results demonstrate that the auditory modulation of tactile roughness perception is strong enough to reach statistical significance across a randomly selected group of participants (rather than among just a subset of participants as reported in Jousmäki and Hari's 1998 study). Given that the participants in our study were unaware of which samples were presented within the experimental presentation device, our results are more likely to reflect genuine multisensory perceptual effects, with minimal contribution from task demands (Choe et al. 1975; Intons-Peterson 1983; Orne 1962; Rosenthal 1967).

However, the direction of the bias reported in experiment 1 is different to that described by Jousmäki and Hari (1998). They reported that high-frequency amplification leads to an increase in reported tactile 'smooth-dryness', whereas in experiment 1 we found that it led to a significant bias towards rough responses (while cutting high frequencies led to a considerable bias towards smooth judgements). There are several plausible reasons for this difference. First, Jousmäki and Hari's use of a composite response scale ('rough/moist-smooth/dry') means that it is unclear which dimension on the scale participants were using when making their response. For example, it is possible that the 'wet/dry' dimension of the composite scale may have been more salient to participants than the 'rough/smooth' dimension. Consequently, participants may have chosen to respond to changes in their perception along the former dimension, at the expense of the latter. Given that a unitary response scale (rough-smooth) was used in experiment 1, there was no opportunity for such task variation in our study.

A second possible reason for the discrepancy is that the auditory frequency manipulations used in experiment 1 may have changed the tactile perception of abrasive surfaces in a manner different to the changes induced at the palmar skin surface. According to this argument, different frequency components may be critical for modulating our perception of different surfaces. Alternatively, it might be that different perceptual attributes contribute to our perception of texture and/or roughness for different surface textures. For example, stickiness, oiliness and clamminess might contribute more to the perception of texture at the palmar skin surface, whereas other perceptual attributes such as hardness, coarseness, and graininess might be weighted more highly in our judgements of the texture of abrasive surfaces (cf. Lederman 1982).

We attempted to resolve this discrepancy between the effects of the sound manipulation in Jousmäki and Hari's

(1998) study and in our own experiment 1, by repeating Jousmäki and Hari's hand-rubbing manipulation while separating out the two response dimensions. In half of the trials, participants were required to respond to the perceived roughness of their hands, while in the remainder of the trials participants responded to the perceived moistness of their hands instead. Given the results of experiment 1, we predicted that the high-frequency boost manipulation would lead to an increased perception of roughness, but would also lead to an increased perception of dryness of the hands. Such a result would be consistent both with the data from experiment 1 and with Jousmäki and Hari's previous results, and would suggest that the 'wetness' component of the composite response scale was more salient than the roughness aspect when rating subjective palmar skin sensation.

Experiment 2

Materials and methods

Participants

Twenty undergraduates participated in experiment 2 (14 men and 6 women, with ages ranging from 19 to 24 years). All were naïve as to the purpose of the experiment and all gave their informed consent prior to their inclusion in the study.

Apparatus

The equalisation, mixer and relay-switching equipment was the same as that used in experiment 1. A microphone (Sennheiser ME66/K6 supercardioid) was mounted inside a sound-attenuated booth such that, when participants were seated in the booth, the microphone was positioned immediately in front of their knees. The output from the microphone was directed through one of three attenuators (Advance Instruments step-attenuator, model A64A) situated outside the booth, and subsequently through one of three equalizers via a computer-controlled relay switchbox. The sounds were then fed back to the participant in the booth, via a pair of headphones (Ross RCB200) powered by the output of the mixer. The amplification was set such that the loudest sounds encountered were approximately 75 dB (i.e. corresponding to a 'comfortable' listening level).

The response scale was presented on a monitor situated outside the sound-attenuated booth at a distance of approximately 50 cm from the participant. The monitor was visible through a window in the booth. Responses were made using a pair of footpedals situated below the participant's feet. The response scale was 25 cm wide, with 100 scale divisions, and semantic anchors were shown at either end of the scale bar. For the wet-dry scale, the 'wet' anchor was shown at the left hand side of the bar, while for the rough-smooth scale the 'rough' anchor was shown in that position.

Design

An anchored magnitude estimation procedure was followed. On each trial, the participant's task was to rate either the perceived wet-dryness or the perceived rough-smoothness of their hands.

A fully crossed Frequency manipulation (attenuated, veridical, or amplified) × Sound attenuation (0 dB, –20 dB or –40 dB) × Response scale (wet-dry, rough-smooth) × Experimental block (8) design was used. Within each block of 18 trials, all possible frequency manipulation, attenuation level and response scale combinations were presented once. The 8 blocks were run consecutively. Frequency manipulations were identical to those described in experiment 1. The 12-dB amplification and/or attenuation (which was the maximum available with the model of equalizers used) was slightly less then the 15 dB used by Jousmäki and Hari (1998) in their study.

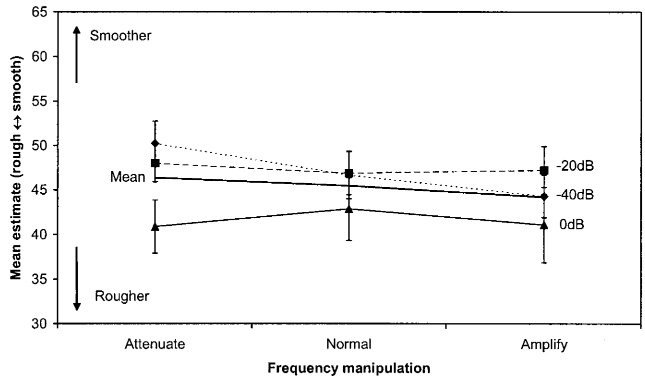
Procedure

Participants were seated comfortably in the sound-attenuated booth with the microphone and response footpedals situated immediately in front of them. They were instructed to rub their hands together above the microphone when cued to do so, and then to rate the subjective sensation of their hands according to the scale dimensions for that trial. It was stressed to participants that the response dimension would vary from trial to trial, and that care should be taken to ensure that they responded along the correct dimension, displayed on the monitor for each trial. The movement of the scale pointer was effected by a pair of footpedals: Participants normally kept both footpedals depressed and moved the pointer to the left by lifting their foot off the left footpedal, and to the right by lifting their right foot. When the participant was satisfied with their subjective rating on a given trial, they pressed a button on the wall of the chamber to advance the experiment to the next trial. No time limits were imposed for the completion of their responses.

A single practice block was provided prior to the 8 experimental blocks in order to allow the participants time to familiarize themselves with the experimental setup. Each block took approximately 5 min to complete.

Results

For each participant, response data – i.e. the subjective ratings of rough-smoothness or wet-dryness – for the 8 experimental blocks were averaged for each of the nine conditions. Subsequently, two separate Frequency manipulation × Sound attenuation repeated-measures ANOVAs a)



b)

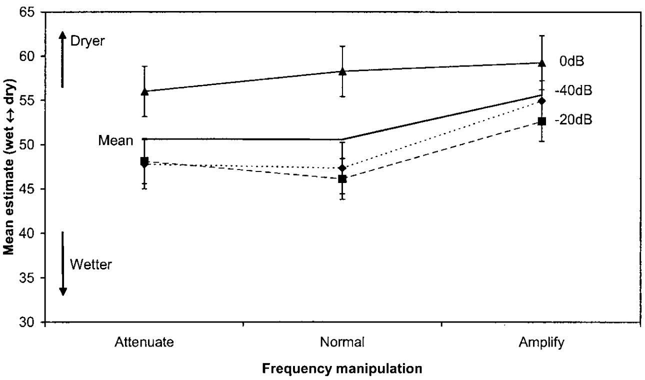


Fig. 3a, b Mean magnitude estimates of **a** rough-smoothness and **b** wet-dryness for three overall-attenuation levels (0 dB, –20 dB, –40 dB) against three frequency manipulations (high-frequency attenuated, veridical audio frequencies and amplified high frequencies) for experiment 2. *Error bars* show ±1 SE

were carried out, one for the wet-dry scale data, and the other for the rough-smooth scale data.

For the rough-smooth analysis, neither of the two main effects were statistically significant (Sound attenuation, $F_{2,18}$=1.24, P=0.312; Frequency manipulation, $F_{2,18}$=0.61, P=0.556), although the Frequency manipulation × Sound attenuation interaction was significant ($F_{4,16}$=3.28, P=0.038). This latter effect, shown in Fig. 3a, is not simple to interpret, but suggests a relatively strong effect of frequency manipulation for the –40-dB attenuation as compared to the other attenuation levels. For this attenuation level, an increase in perceived roughness is seen from attenuated through veridical to amplified sound conditions. None of the other attenuation levels show clear variation across the different frequency manipulations. Of all possible pairwise comparisons, only that between the mean roughness ratings for high-frequency attenuated and high-frequency amplified sounds, for the –40 dB overall attenuation level, was statistically significant. This result is consistent with the high-frequency amplification leading to a rougher perception of the palmar skin than for either the veridical or the high-frequency attenuated manipulations.

For the wet-dry analysis, the effect of Sound attenuation ($F_{2,14}$=4.48, P=0.026), Frequency manipulation ($F_{2,14}$=15.25, P<0.001) and the Frequency manipulation × Sound attenuation interaction ($F_{4,16}$=3.08, P=0.047) were all statistically significant. The effect of sound attenuation indicated that the loudest sounds led to the driest perceptions (mean wet-dry rating 57.9) as compared to the –20 dB attenuation (mean 49.0) or –40 dB attenuation (mean 50.0). Post hoc tests indicated that the difference between 0 dB and either of the other two attenuation conditions was significant. Figure 3b illustrates the effects of frequency manipulation and the nature of the interaction. High-frequency amplification led to drier perceptions as compared to the other sound manipulations (amplified, mean 55.6; veridical, mean 50.6; attenuated, mean 50.6); the amplified condition led to significantly higher (i.e. drier) ratings than either of the other sound manipulations, which did not differ. Once again, the interaction is more difficult to interpret. It appears that the loudest (0 dB) sounds have a different pattern of variation in wet-dryness across the different frequency manipulations as compared to the two quieter conditions; there is minimal variation by frequency manipulation for the loudest sounds, whereas for the other two overall attenuation levels, post hoc tests revealed that the high-frequency amplification led to significantly drier ratings than the other two frequency manipulations, which did not differ. The lack of effect for the 0 dB attenuation is unlikely to be a ceiling effect, since the mean ratings are well inside the perceptual scale's range. Overall, these results are consistent with those of Jousmäki and Hari (1998), the only difference being that veridical and high-frequency attenuated sound conditions behaved very similarly according to the data reported here.

Note that the participants in our study performed more trials than those who took part in Jousmäki and Hari's (1998) study. We were therefore able to analyse whether the strength of the parchment-skin illusion changes with time on task. This was investigated by plotting magnitude estimates against time for a subset of conditions (Fig. 4). Inspection of these graphs suggests that responding to the wet-dry scale changed minimally over experimental blocks, whereas there is an indication that the rough-smooth ratings gradually decrease (i.e. become rougher) over time. These trends were tested by performing 6 separate repeated-measures ANOVAs with block number as the independent variable, for all 20 participants' data, individually collapsed as in Fig. 4. Only one significant effect of block was revealed, in the high-frequency attenuated data for the rough-smooth judgements ($F_{7,13}$=2.95, P=0.044; see Fig. 4a). However, post hoc analysis revealed no reliable differences in pairwise comparison of blocks, nor any polynomial trends which provided a statistically significant fit to the data (best fit, linear trend: $F_{1,19}$=3.36, P=0.082). Therefore it appears that any time-based effects are ephemeral in nature; the parchment-skin illusion does not decrease significantly in

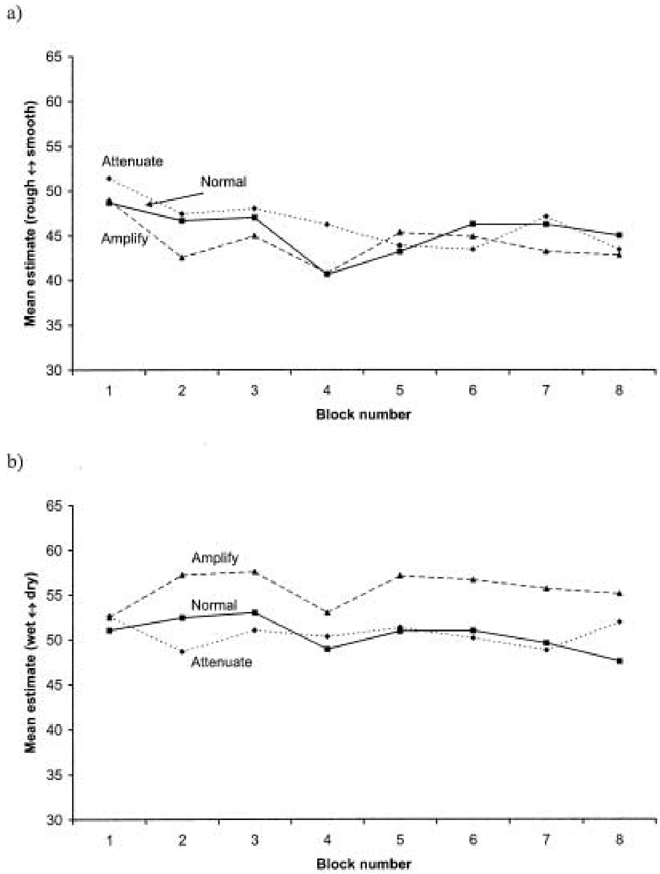


Fig. 4a, b Experiment 2, variation of mean magnitude estimates over consecutive experimental blocks, for the three frequency manipulations collapsed across all overall-attenuation levels

magnitude with continued exposure, at least within the temporal durations tested here.

Discussion

Experiment 2 clearly replicates (and provides an explanation for) two results which appeared to be in conflict at the end of the previous experiment: Namely, that smoother sensations arise from high-frequency attenuation (experiment 1) of tactile sounds and that high-frequency amplification leads to the same change in sensation (Jousmäki and Hari 1998). In the first instance, if we consider only the wet-dry scale results, we find agreement with the results of Jousmäki and Hari. That is, the subjective sensation of skin dryness was enhanced with high-frequency amplification and with overall increases in sound volume. On the other hand, if we consider the rough-smooth scale results, we see that, although the effects are less clear, these are generally consistent with experiment 1, i.e. high-frequency amplification led to rougher subjective sensations. These results suggest that moistness is a more salient perceptual dimension for skin perception than roughness (since all effects in the former perceptual dimension reached statistical significance, whereas the main effects in the roughness assessment analysis did not). Moreover, the salience of wetness over roughness is further indicated by Jousmäki and Hari's results, since if the two dimensions were equally salient no overall perceptual effects would have been reported in their experiment. This follows from our finding in the current experiment that these dimensions provide opposite directions of effect, at least when larger magnitude estimates were assigned to smoother and drier individual response scales. Of course, one could devise a 'smoother/wetter-rougher/drier' composite scale, which would better reflect the patterns of perception we find here; although one would still be unable to determine the relative magnitude of the effect upon the two individual perceptual dimensions which form this new composite measure.

Note that, unlike Jousmäki and Hari (1998), we did not normalise our raw response scale scores prior to analysis, because the within-participant normalisation of the type used by Jousmäki and Hari makes untestable assumptions about how different people use the response scale. Specifically, it assumes that the same psychological meaning is attached to an individual's extreme responses, regardless of the actual value of such extremes. Normalisation of the triad of values (4, 5, 6) leads to the same transformed scores as normalisation of the triad (1, 5, 10), namely the scores (0, 0.5, 1). This normalisation is only valid if, for example, '4' in the first triad has the same psychological meaning as '1' in the second. Such subjective meanings are objectively untestable. Moreover, one of the tenets of magnitude estimation is that the reported values do indeed represent the size of perceptual effect (Haverland 1979; Westermann 1982).

Jousmäki and Hari (1998) have informally noted in their brief report that introducing a delay of more than 100 ms between rubbing the hands and receiving the audio feedback from the hands appeared to destroy the parchment-skin illusion. Formally replicating such a temporal asynchrony effect would add weight to the argument that the parchment-skin illusion is indeed perceptual in nature – rather than based on task demands – for two main reasons. First, participants are unlikely to have an a priori expectation of what effect delaying sound feedback 'should' have upon tactile sensation. Second, multisensory binding is typically broken by cross-modal delays that exceed approximately 75–120 ms (Bertelson and Aschersleben 1998; Calvert et al. 1998; Driver and Spence 2000). Therefore, any degradation of the parchment-skin illusion uncovered by adding audiotactile delay would suggest that audio and tactile percepts were being combined during the illusory sensation. Our final experiment included three discrete levels of audiotactile delay to formally test Jousmäki and Hari's (1998) claims.

Experiment 3

Materials and methods

Participants

Twenty subjects participated in experiment 3 (8 men and 12 women, with ages ranging from 19 to 31 years). All were naïve as to the purpose of the experiment and all gave their informed consent prior to their inclusion in the study.

Apparatus, design, procedure

The equipment set-up remained as in experiment 2, except that in this experiment the attenuator feed-out loop was replaced by an audio delay box (Pixel Instruments Corporation, model AD2100). This device allows a continually operating, fixed delay to be applied to an audio signal. In this case, a 150-ms delay was set for both channels (i.e. left and right). One audio path bypassed the box (i.e. provided a 0-ms delay path), a second path was fed once through one channel of the device to provide the set 150-ms delay and a third path was looped sequentially through both channels, giving a cumulative delay of 300 ms. Since the delay box slightly attenuated sounds on each feed-through, step-attenuators were added to the 0-ms- and 150-ms-delay paths, to allow audio loudness to be equated across all delay conditions. The signal path to the equalisers remained identical to that described in experiment 2, as did all aspects of the experimental procedure.

Results

Data were analysed in similar fashion to experiment 2. Two separate Frequency manipulation × Delay repeated-measures ANOVAs were carried out, one for the wet-dry scale data, one for the rough-smooth scale data. For the rough-smooth data, the two main effects were statistically significant. The Frequency manipulation effect ($F_{2,18}$=7.96, P=0.003) indicated that high-frequency amplification led to rougher perceptions (mean 37.0) as compared to veridical sound (mean 49.1), whereas high-frequency attenuation led to smoother perceptions (mean 58.7). Post hoc tests indicated that only the difference between veridical and high-frequency amplified conditions was statistically significant. For the Delay effect ($F_{2,18}$=3.58, P=0.049), comparing delayed conditions with the no-delay condition (mean 46.7) indicated that the 150-ms (mean 50.2) and 300-ms (mean 48.1) conditions led to less rough percepts as compared to the no-delay condition. Only the pairwise difference between the former two conditions was significant. The Frequency manipulation × Delay interaction was not statistically significant ($F_{4,16}$=2.28, P=0.106).

For the wet-dry analysis, there were again significant effects of Frequency manipulation ($F_{2,18}$=4.19, P=0.032) and Delay ($F_{2,18}$=10.18, P<0.001), but no interaction ($F_{4,16}$=0.86, P=0.509). The effect of frequency manipulation echoed that found in experiment 2, where high-frequency amplification led to drier perceptions (mean 67.0) as compared to the normal sound (mean 58.5), which itself led to drier perceptions than the frequency-attenuated sound (mean 48.5). Considering the effect of delay, compared with the no-delay condition (mean 61.1), both 150-ms (mean 55.1) and 300-ms (57.6) delays weakened the perception of dryness for the hands. Again, only the pairwise comparison between the no-delay and 150-ms delay was significant.

Discussion

Jousmäki and Hari (1998) informally report that adding a delay between the touching event and the audio feedback from that event reduces the strength of the parchment-skin illusion. The analysis reported here confirms that. Introducing a 150-ms delay led to significant decreases in the effect of frequency manipulation upon both scales' mean magnitude estimates. This further suggests that the perceptual effects reported are genuine, rather than demand-characteristic based, since the experimental demands remained constant, and participants presumably had no a priori expectation of what effect sound-lag 'should' have upon tactile sensation (cf. Calvert et al. 1998; Driver and Spence 2000).

An interesting effect in the delay data is that the 300-ms delay conditions (in contrast to the 150-ms delay condition) did not lead to clear changes in perceptual estimates as compared to the no-delay conditions. This seems unexpected, since a larger lag would generally be expected to reduce the cross-modal illusion to a degree that was at least as great, if not greater, than that reported at the shorter delay. The reason for this lack of effect may lie in the periodic nature of the hand-rubbing sounds. If the time for the traversal of one palm against the other is ~300 ms, then the 300-ms delay will actually bring the sound feedback and hand-rubbing motion back in phase, or at least the sounds at the hand 'turning points' will be in phase with the appropriate hand position. If these points are critical in fusing the audio and tactile inputs into a unified percept – more critical than the between turning-point sounds – then less dramatic effects of the 300 ms would be expected.

To informally test the above hypothesis, hand-rubbing sounds from a small number of individuals were recorded after the experiment and the sound spectral profiles examined. Analysis of these waveforms suggested that the period for hand-rubbing is within a range such that the above explanation could apply, although a detailed, participant-wise analysis would be required for any definite statement to be made. During the experiment, recordings were not made of participants' hand sounds and so the data were not available to allow such an analysis. This 'phase dependency' account is clearly post hoc in nature, and the issue warrants further research.[2]

Note that this experiment reported a significant effect of frequency manipulation upon rough-smooth, as well as wet-dry ratings, a result which was not so clearly evident in experiment 2. However the significant rough-smooth effects seen here are consistent with the (nonsignificant) trends suggested by the previous experiment.

General discussion

Sound is a ubiquitous concomitant of the majority of our interactions with objects in the world around us (Gaver 1993a, 1993b), but does it actually contribute to our perception of such objects? Previous research has provided contradictory results (Jousmäki and Hari 1998; Lederman 1979). The most parsimonious account of the majority of research to date appears to be that, while people can discriminate between different objects and/or surfaces on the basis of their sounds (Freed 1990; Katz 1925; Lederman 1979; Warren and Verburgge 1984; Wildes and Richards 1988), participants typically tend to weight tactile cues more heavily when combined audiotactile information is available (Lederman 1979). Jousmäki and Hari's brief report provides the most convincing evidence to date that manipulation of auditory feedback can significantly alter people's texture perception; however, their seminal study suffers from a number of methodological and interpretational limitations. Nevertheless, the results reported here demonstrate clearly that auditory cues can significantly change tactile texture perception along the dimensions of roughness and wetness, and for abrasive papers and the palmar skin surface.

In relation to the two perceptual dimensions investigated in experiments 2 and 3, we note that, according to the perceptual scaling work of Hollins et al. (1993, 2000), of these dimensions, only roughness appears to be fundamental in tactile texture perception. Despite this, participants can clearly make meaningful ratings along the dimension of wetness, and effects of frequency manipulation are reflected in such ratings. Indeed, even though wetness is a dimension that does not 'naturally' emerge through the perceptual scaling of tactile textures, this does not preclude its importance in a more general sense. For example, similar scaling work upon visual textures by Rao and Lohse (1996) reveals that the fundamental dimensions with respect to (scaling of) visual texture are quite different to the dimensions which are fundamental in the visual system in general (i.e. luminance, colour). The meaning of 'fundamental' thus appears to vary with task context. It is also possible that 'wetness' (partially) encompasses the 'sticky/slippery' dipole which emerges as a possible tertiary dimension in the studies of Hollins et al. (1993, 2000).

The loudness of the auditory feedback generated when people feel a textured surface is dependent on the force with which people touch the surface (Lederman 1979), with increasing force resulting in louder feedback. Moreover, Lederman and Taylor (1972) have also reported that increasing the force with which a surface is touched leads to an increased perception of the roughness of that surface. Consequently, one might expect that amplifying touch-related auditory feedback would result in the increased perception of roughness of a touched surface, and that the attenuation of auditory feedback might lead to an increased perception of smoothness.[3] However, the parchment-skin illusion appears to be capable of working in the opposite direction, suggesting that the frequency content of touch-produced sounds may be the dominant factor in audiotactile perceptual interactions.

Many further questions remain to be answered in the area of audiotactile interactions in texture perception, perhaps the most important of which is whether there are any frequency components that are specifically associated with tactile roughness, smoothness or other textural properties. For instance, do most smooth surfaces have some common, spectrally powerful components? Any such associations could be learned developmentally as the individual interacts (i.e. touches and hears) the objects around them. At present, the manipulations used (i.e. high-frequency boost or cut) are of uncertain ecological validity (cf. Gaver 1993a, 1993b). Manipulations following a more ecological approach (Freed 1990; Warren and Verbrugge 1984), or created by actually presenting rough-surface sounds while people touch smooth surfaces or vice versa would enable any sound-touch interactions to be grounded more firmly in an ecologically relevant context (such manipulations are far more practicable in the context of visual-tactile interactions in texture perception). Furthermore, it is also important to note that modulation of the auditory frequency spectrum is only one approach to the modulation of roughness, of which there may be others. For example, researchers have shown that auditory roughness perception can also be related to the 'time-structure' of sounds, with stronger time-structure leading to the increased perception of roughness (Terhardt 1974; Vogel 1974).

We believe that multisensory texture perception provides a paradigm case for the study of multisensory integration, given the contribution of tactile, auditory,

[2] Note that the introduction of an asynchrony might not be expected to have as detrimental an effect in the present study as in previous audiovisual studies, the reason being that our participants presumably still knew at some level that the sounds that they heard referred to their own hand-rubbing, given that they initiated the events that elicited the onset of the hand-rubbing sounds. This contrasts with previous studies that have introduced audiovisual asynchrony, where the only reason participants had to link, e.g. a pure tone and a flashing light, was their temporal proximity.

[3] One particularly interesting avenue for future research here would be to investigate whether people modulate the force with which they touch a surface in response to the loudness of the auditory feedback they hear. Such a result would imply an even more important role for sound in our interactions with the world (cf. Gordon and Cooper 1975).

visual and even olfactory cues to our perception of texture (Christensen 1983; Fiore 1993; Lederman 1982). Despite the lack of proven ecological validity associated with the particular sound manipulations used in this and previous studies of audiotactile interactions in texture perception (Jousmäki and Hari 1998; Lederman 1979), the fact remains that our results provide a 'proof of principle' that modulating the sounds associated with touching a surface can modulate people's perception of the texture of the surface which they are touching.

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