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Tactile roughness and the "paper effect"

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It has previously been shown that the apparent roughness of a surface is enhanced when the surface is felt through a piece of paper that moves with the fingers. The present experiment reveals that the "paper effect" cannot be generalized to all types of surfaces and that the criterion for roughness plays a role in obtaining it. The specificity of the effect is discussed in terms of the stimulus properties that may underlie the sensation of roughness.

The most elementary question pertaining to tactile roughness, namely, what is its adequate stimulus, has so far escaped answer. Perhaps the single most important step toward answering this question was taken recently by Taylor and Lederman (1975), who showed that the parameters of a surface that affected the amplitude of skin displacement also affected the perception of roughness. Complementary to this finding was an earlier result from the same researchers that indicated that perceived roughness varies directly with applied force (Lederman & Taylor, 1972). Presumably, pressing the finger more firmly against a surface causes the skin to conform more completely to the irregularities in the surface, which results in a stronger sensation of roughness.

Yet it is this simple relationship between displacement and perceived roughness that stands in contradiction to the results of a recent study by Lederman (1978b). In that study, Lederman was able to show that the sensation of roughness increased when a layer of paper was inserted between the skin and the surface. Such a result seems inconsistent with the notion that amplitude of displacement plays a crucial role in the sensation of roughness. Insertion of a medium between the sense organ and the stimulus should reduce the amplitude of skin displacement and, thereby, attenuate the sensation of roughness. The paradoxical nature of these findings sparked interest in what will here be called the "paper effect," and the present study was designed to examine the validity of the effect.

Lederman's (1978a, 1978b) initial study of the paper effect grew out of an experiment conducted by Gordon and Cooper (1975). In their study, Gordon and Cooper demonstrated that the orientation of a small (.0127 mm in height) undulation was better discerned when, instead of feeling the surface with a bare fingertip, subjects felt the undulation through a thin sheet of paper. Crucial to the success of the experiment was movement of the intervening paper with the finger as it scanned the surface. Gordon and Cooper theorized that perception of the undulation improved because the paper reduced the sensation of roughness that would normally arise from the lateral motion between the skin and the surface. Specifically, the investigators wrote that when feeling with the bare skin, "a highly sensitive system, such as that associated with light pressure, may interfere with the input from deeper pressure receptors, the response to roughness thus masking the response to more gradual surface changes" (Gordon & Cooper, 1975, p. 204).

Lederman (1978b) subsequently put this hypothesis to test, reasoning that "Gordon and Cooper must predict that the perceived roughness of their surface, or any surface for that matter, will decrease when the paper is used" (p. 154). Using sandpaper covered by a layer of writing paper as stimuli, Lederman proceeded to show exactly the opposite: Magnitude estimates of roughness were larger when the stimuli were felt through a second layer of paper that moved with the fingers. To explain the surprising result, Lederman modified Gordon and Cooper's (1975) hypothesis: She agreed that lateral or shear forces mask or inhibit the perception of normal (vertical) forces. However, because of the earlier work that pointed to normal forces as being the stimulus for roughness (Lederman & Taylor, 1972; Taylor & Lederman, 1975), Lederman hypothesized that the shear forces did not themselves trigger a sensation of roughness. Hence, normal forces produce roughness, whereas shear forces only inhibit it. The additional layer of paper therefore served to "unmask" the sensation of roughness. This "shear" interpretation of the paper effect appeared to gain stature in additional experiments in which the stimuli were fields of spherical beads manipulated to produce greater or lesser amounts of shear forces (Lederman, 1978a).

The present experiment evolved from an attempt to verify Lederman's (1978a, 1978b) findings: Feeling bare sandpaper both with and without an intervening (moving) piece of paper brought contradictory results. The surfaces felt rougher when scanned with bare fingers than when scanned through a layer of paper. From this came the idea that the paper effect might

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apply only to certain kinds of surfaces (e.g., "covered" but not "bare" sandpaper), an idea that the present experiment confirms. The results show that the effect may work for surfaces composed of relatively low spatial frequencies but that it fails for more complex surfaces. An alternative interpretation of the paper effect is offered that helps rectify the seeming discrepancy between the results of Lederman and those of Gordon and Cooper (1975).

METHOD

Apparatus and Procedure

Because casual experiments with bare sandpaper failed to yield the paper effect, it was decided that two types of surfaces should be tested: bare sandpaper (the "bare" condition) and sandpaper covered with a layer of paper (the "covered" condition). The covered condition was comparable to Lederman's (1978a, 1978b) stimuli, and, to that end, initial attempts employed plain writing paper approximately 100 microns thick.[1] However, for the main experiment, paper was replaced by a covering of Scotch 810 Magic Tape (approximately 80 microns) after it was established that the paper effect was obtainable with either paper or tape. The tape provided superior adhesion to the sandpaper surface.

The stimuli were composed of 3-in. squares of sandpaper (grit numbers 36, 50, 60, 80, 100, 150, and 220) glued to 3-in. squares of cardboard. In the covered condition, two contiguous pieces of tape (together forming a strip 38 mm in width) were adhered side by side across the middle of the sandpaper. The stimuli rested on a modified balance to control applied force at 120 g, and they were shielded from the subjects' view by an occluding screen. Subjects felt the surfaces by aligning the base of the index finger of the right hand in a groove on the balance and then bringing the distal fingerpad down to contact the surface with enough force to tip the balance. The surface was felt by drawing the fingertip across the sandpaper (toward the subject) in a single motion. Subjects received practice with a blank piece of cardboard until they could reliably move their index fingers across the surface at an approximately constant rate (approximately 5-8 cm/sec).

The experiment had two parts. In the first half of a session, subjects felt either only bare sandpaper or only covered sandpaper, followed by the remaining condition in the second half. Pilot work demonstrated the necessity for testing only one type of surface at a time because of the inability of subjects to maintain a consistent criterion for roughness across the two types of surfaces. A mixed design in which covered and bare surfaces were felt successively by bare and covered fingers yielded no paper effect for either type of surface. (This problem is considered in more detail in the discussion section.) Lederman's (1978a, 1978b) effect returned when subjects concentrated on only one texture at a time (order of presentation counterbalanced across subjects) with a brief (5-min) break between conditions. Subjects scanned each of the seven bare and seven covered surfaces four times: twice with the bare index finger and twice with the fingerpad covered with a strip of tape. The finger was bare (or covered) on no more than three consecutive trials, and the grits were presented in random sequence.

Instructions to the subjects were simply to assign numbers on each trial that described the magnitude of the sensation of roughness they felt. Between session halves, the subjects were told that the surfaces they would feel next might appear different in texture from the previous surfaces but that they should assign numbers to the sensations that were consistent with numbers assigned to the preceding stimuli. That is, if the second set of surfaces tended to feel rougher than the first, they should, in general, assign larger numbers, and vice versa. The first three trials in each half of the session were discarded as practice trials. Subjects listened to white noise through headphones to mask the sound caused by friction between the subjects' fingers and the sandpaper surfaces.

Fifteen college students (4 males and 11 females) served as subjects, each contributing two estimates of roughness per stimulus, to yield a total of 30 observations per data point.

RESULTS AND DISCUSSION

Figure 1 displays the geometric means of the roughness estimates for the four conditions of the experiment. The data are plotted as a function of the reciprocal of grit number, yielding a dimension that is proportional to the diameter of the sandpaper particles. The dashed line separates results for the bare and covered sandpaper conditions, illustrating the unsurprising fact that bare sandpaper feels rougher than tape-covered sandpaper, whether or not the exploring finger is itself covered. We can safely say that bare sandpaper is a more effective stimulus for roughness than is covered sandpaper.

The most important finding of the experiment, however, is that the sensation of roughness is greater when bare skin contacts bare sandpaper. This result is the opposite of the paper effect and conforms to the naive expectations that a layer of paper (tape) should hinder the perception of a textured surface.

Below the dashed line in Figure 1 lie the data for the covered sandpaper surfaces, for which the paper effect reappears. That is, when the stimulus is sandpaper covered by tape, the surface feels rougher when felt through another layer of tape than it does when felt with a bare finger. The experiment therefore demonstrates that the paper effect occurs, but only on certain types of surfaces.

To understand why the paper effect occurs in some

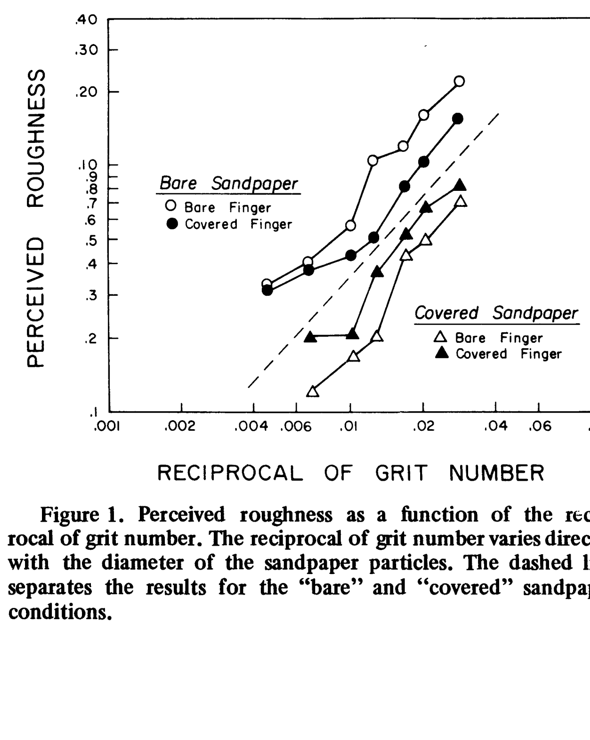

Figure 1. Perceived roughness as a function of the reciprocal of grit number. The reciprocal of grit number varies directly with the diameter of the sandpaper particles. The dashed line separates the results for the "bare" and "covered" sandpaper conditions.

cases but not others, it is helpful to consider two factors that are central to the psychophysical assessment of tactile roughness: surface geometry and the criteria for roughness.

Surface geometry obviously plays a key role. Sandpaper has a highly complex surface owing to the irregular shapes of and spacings among the particles that compose it. This irregularity means that the surface contains a wide range of spatial frequencies. In addition, the abrasive qualities of the surface provide the potential for significant friction and shearing forces. Covering the surface with paper (as Lederman, 1978a, 1978b, did) changes this: Because of its stiffness, the paper acts as a low-pass filter, eliminating the highest spatial frequencies while attenuating the amplitude of the remaining lower frequencies. The removal of high spatial frequencies means that the covered surface contains no sharp edges and should, consequently, produce less friction between the finger and surface. By all accounts of what produces roughness (i.e., amplitude variations or shear forces), a paper-covered surface should feel smoother than a bare surface. Figure 1 bears this out.

Now consider the effect of covering the finger instead of the sandpaper. Adding tape to the finger should have the same general effect as adding tape to the surface. That is, the tape acts as a low-pass spatial filter and prevents the skin's conforming to the higher spatial frequencies of the surface. Accordingly, friction and shear should be attenuated, although with only the finger covered, the opportunity remains for the sharp edges of the surface to dig into and "catch" on the tape. Some of the shear forces caused by this abrasive action are undoubtedly transmitted to the skin and may give rise to sensations of roughness. Nevertheless, the overall effect should once again be to reduce the sensation of roughness relative to the bare-finger/bare-sandpaper condition, and the data confirm this.

Finally, consider what should happen when tape covers both the finger and the surface. Because the spatial frequency of the surface has already been filtered once by the static layer of tape, the second layer added to the finger should have little additional effect on the vertical component of the stimulus. This is because the mechanical properties of the two layers of tape are virtually identical, so that much of what gets through the first layer of tape will also get through the second. The major effect of the second layer probably is, as Lederman (1978a, 1978b) states, to reduce the friction and shear normally generated by running the finger over the tape-covered surface. That is, relative motion between the two smooth tape surfaces should produce less friction than relative motion between the skin (with its dermal ridges) and the tape. It may be recalled that because roughness was enhanced in that condition relative to the bare-finger/covered-sandpaper condition, Lederman proposed that friction was not itself a stimulus for roughness but only interfered with the perception of normal forces.

Another explanation is possible. Essentially, the covered-sandpaper stimulus is composed of randomly distributed low-frequency undulations in a superficially smooth surface. Feeling such a surface with bare fingers should produce significant vertical displacements of the skin, along with lesser shear forces set up by friction between the tape and the skin. It seems likely, however, that the shear forces are largely independent of the undulations (i.e., the skin probably does not "catch" on the more gradual spatial gradients of the surface). Shear and its concomitant tactile sensation would in this case be uncorrelated spatially with the normal forces produced by the undulations and might act primarily to provide a background "noise" relative to the variations in pressure sensation. Furthermore, the frictional sensation might well be interpreted correctly by the subject as merely the texture of a material (tape or paper) that overlays the nominal stimulus, the undulations. As such, the shear forces could hardly be expected to contribute to estimates of roughness.

This interpretation is merely an enlargement of Gordon and Cooper's (1975) explanation, applied here to perception of roughness rather than to perception of a single undulation. The hypothesis rests on the notion that both shear and normal forces can contribute to sensations we commonly label as roughness, but for the sensation of roughness to rise in the presence of shear forces may require that the spatiotemporal patterns of shear and compression forces be correlated. The best example of this may be bare sandpaper, which produces normal and shear forces that are highly correlated spatially, and which proved to be the most effective stimulus for roughness in the present experiment.

The criterion for roughness may provide a second reason why in some cases shear forces seem inhibitory to roughness. In Lederman's (1978a, 1978b) experiments, what changed most with grit size (the independent variable) was the height of the undulations in the paper. It therefore seems reasonable to propose that the task facing the subject was basically the same in both Gordon and Cooper's (1975) and Lederman's experiments: to detect low-frequency undulations. Yet it is arguable whether or not the sensation evoked by fields of low-frequency undulations qualifies as the prototypal sensation of roughness. Subjects in the present experiment, all of whom felt both covered and uncovered surfaces, were asked to characterize the sensation produced by the two types of surfaces (which they had not seen). Whereas bare sandpaper was most often described as "rough," "abrasive," "gritty," or "causing friction," an overwhelming number of subjects described the covered sandpaper as simply "bumpy," and in one case, "smooth and bumpy." Clearly, the sensations produced in the two conditions were different, were probably owing to different types of stimulation (i.e., predominantly perpendicular versus both perpendicular and lateral), and yet, because of the design of the present experiment, were both scaled as roughness.

The significance of the criterion problem revealed itself during the first attempt to measure the roughness of both covered and uncovered surfaces in a mixed design. When subjects judged the roughness of bare and covered sandpaper together, the effect disappeared. Subjects typically complained that they were unable to compare and rate the dramatically different sensations that the two surfaces induced. In short, they failed to establish a stable criterion for roughness. In Lederman's (1978a, 1978b) experiment, faced with only one type of surface, subjects could not be similarly confused. But in the present study, the freedom to change criteria midway through the session led to the finding that surfaces that produce a high degree of shear and friction are sometimes rated as very rough.

By way of summary, it has been shown (1) that the paper effect cannot be generalized to all types of surfaces, (2) that reduction of shear forces probably does render perpendicular forces more perceptible (i.e., Lederman's, 1978a, 1978b, results were confirmed), (3) that shear and frictional forces may nevertheless contribute significantly to sensations we commonly label as roughness, and (4) that the criterion for roughness is easily altered by experimental design. The net result is, unfortunately, a rather negative one: There exists no definitive description of the sensation of roughness, nor of the stimuli that evoke it. What progress has been made must now be followed with careful experimentation that takes into account the problems of criterion and stimulus specification. Perhaps analyses based upon the concept of spatial frequencies will provide a better description of the complex spatiotemporal patterns that yield sensations of roughness.

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NOTE

1. The reported thickness of the writing paper used in Lederman's (1978a) experiments was incorrect (Lederman, Note 1). Typical writing paper has a thickness of nearly 100 microns, compared with the 1- to 4-micron thickness reported in those experiments.

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