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Effects of surface texture and grip force on the discrimination of hand-held loads

J. RANDALL FLANAGAN
Queen's University, Kingston, Ontario, Canada

and

ALAN M. WING
MRC Applied Psychology Unit, Cambridge, England

In this paper, we report the results from two experiments in which subjects were required to discriminate horizontal load forces applied to a manipulandum held with a precision grip. The roughness (and hence friction) of the grip surfaces and required grip force were manipulated. In the first experiment, subjects were instructed to judge the load while maintaining hand position and not letting the manipulandum slip. It was found that performance was influenced by surface texture; a given load was judged to be greater when the surface texture was smooth than when it was rough. This result is consistent with a previous study based on lifting objects and indicates that the effect of surface texture applies to loads in general and not just to gravitational loads (i.e., weight). To test whether the load acting on a smooth object is judged to be greater because the grip force required to prevent it from slipping is larger, a second experiment was carried out. Subjects used a visual feedback display to maintain the same grip force for smooth and rough manipulandum surfaces. In this case, there was no effect of surface texture on load perception. These results provide evidence that perceived load depends on the grip force used to resist the load. The implications of these results in terms of central and peripheral factors underlying load discrimination are considered.

A notable aspect of the hand's versatility in subserving perception as well as action is that its motoric function allows the perception of object attributes some of which cannot be appreciated by vision alone. Perception and action by the hand are, of course, intimately linked. Although skilled manipulation depends critically on the perception of object properties such as weight and surface texture, the way in which an object is handled will determine, in large part, the efficacy with which various kinds of information about the object can be obtained. Thus, Lederman and Klatzky (1987) have shown that subjects adopt different manipulation strategies depending on the perceptual information they are instructed to gather. A key question in understanding the coupling between perception and action is whether motoric aspects of object manipulation affect perception. In this paper, we demonstrate that a perceptual function—discrimination of load—is influenced by an aspect of motor function—the grip force used to hold an object with the tips of the index finger and thumb at its sides (i.e., with a precision grip). Grip force prevents the object from slipping under load force applied orthogonally to the grip axis. Grip force was manipulated in two ways: by varying the surface texture of the object and by explicit instructions to the subject.

Weber's (1834/1978) early demonstration that weight discrimination is better when one is actively lifting an object than when one is passively supporting it suggests that muscle exertion enhances the perception of weight (Bell, 1834), and many studies have since confirmed the importance of muscle activation in weight and force perception (see Jones, 1986, in press, for reviews). Most of these studies have focused on the activity of muscles directly involved in supporting the load. Recently it has been shown that perceived heaviness of a load supported by one finger can be increased if other fingers must support an independent load. However, if the second load is supported by a more remote part of the anatomy, such as a toe, there is no effect on the perceived heaviness of the finger-supported load (Kilbreath & Gandevia, 1991). This suggests that muscle activity that is indirectly involved in lifting may also contribute to weight perception. Might one such class of related muscle activity be grip force?

When an object is held with a precision grip, grip force normal to the contact surfaces allows the generation of a frictional force that prevents the object from slipping from grasp due to load forces tangential to the grip surfaces. The greater the load acting on the object, or the more slippery the contact surface, the greater the grip force required to prevent slip. In a series of studies, Johansson and Westling (1984a, 1984b, 1987; for reviews see Johansson and Cole, 1992, 1994) have shown that, when one is lifting an object with a precision grip, grip force is finely scaled to its surface texture and weight in such a way that the grip force is just slightly greater than the

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This research was supported by a Wellcome Research Travel Grant to J.R.F. Correspondence should be addressed to J. R. Flanagan, Department of Psychology, Queen's University, Kingston, ON, Canada K7L 3N6 (e-mail: flanagan@pavlov.psyc.queensu.ca).

minimum required. In the case of lifting, the load acting on the object is gravitation and is simply the weight of the object. However, Johansson and colleagues (Johansson, Hager, & Riso, 1992; Johansson, Riso, Hager, & Backstrom, 1992) have demonstrated that grip force is also precisely tuned for surface texture and load when variable horizontal pulling loads are applied to the object. Furthermore, Flanagan and colleagues (Flanagan & Tresilian, 1994; Flanagan & Wing, 1993; Flanagan, Tresilian, & Wing, 1993; for a review, see Wing, in press) have shown that grip force is increased in anticipation of load forces that arise from arm kinematics and that these change with surface texture (Flanagan & Wing, 1995). Given the possibility that muscle activity involved only indirectly in lifting may affect perceived weight, as suggested by Kilbreath and Gandevia (1991), changes in grip force induced by changes in surface texture might alter perceived heaviness.

We investigated this possibility in a study in which subjects were required to discriminate between the weights of objects grasped with a precision grip (Flanagan, Wing, Allison, & Spencely, 1995). We observed that objects covered in smooth, more slippery, satin were judged to be heavier than objects of the same weight covered in rough, less slippery, sandpaper. To rule out the possibility that the effect was due to surface texture per se, a control study was carried out in which the objects were grasped using a variant of the precision grip with the thumb underneath and index finger on top. With this grasp, differences in grip force would be not expected as a function of texture and, in fact, there was no effect of texture on perceived weight under these conditions. These results led us to suggest that a smooth object is judged to be heavier than a rough object because the grip force required to hold it is greater.

The hypothesis that grip force influences perceived weight predicts that if subjects were to employ the same grip force when lifting weights with different surface textures, texture should not influence perceived heaviness. The principle objective of the present study was to evaluate this prediction. Subjects were asked to discriminate between reference and test loads applied to a hand-held manipulandum instrumented to measure grip force and load force. In the first experiment, which served as a control study, no instructions were given about grip force, and thus grip force was scaled to the magnitude of the load and the surface texture. The aim of this experiment was to establish whether the effects of surface texture observed when subjects were discriminating between weights (Flanagan et al., 1995) would also be observed when they were discriminating between pulling loads. If so, this result would indicate that the effects of texture are not restricted to gravitational loads (i.e., weights) but generalize to other loads as well (cf. Ross & Brodie, 1987). In the second experiment, visual feedback of grip force was provided and subjects were asked to maintain the same, elevated, grip force across surface textures. If the effect of surface texture on perceived weight (and load), observed under normal conditions, is due to changes in grip force, the effect should be eliminated when the grip forces used to grasp the different textures are matched.

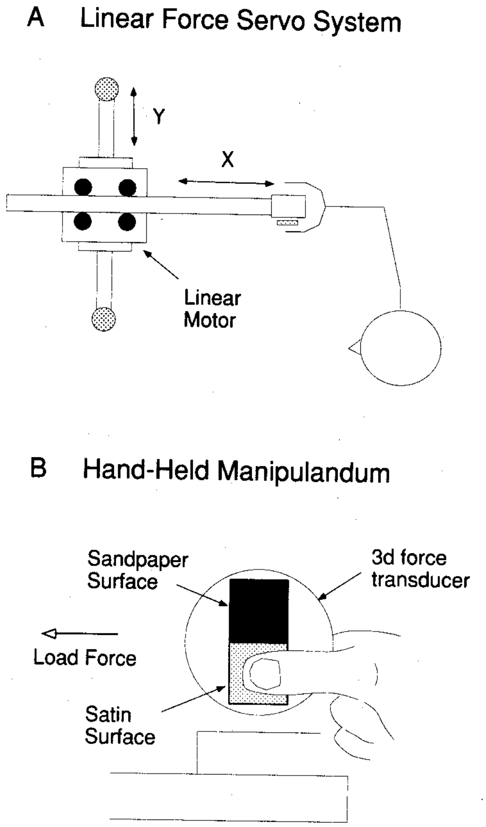

Figure 1. (A) Top view schematic of the linear motor used to deliver pulling load forces to the hand-held manipulandum. (B) Side view of the hand-held manipulandum instrumented with a 3-D force sensor to measure both pulling force and grip force normal to the surface of the object. Subjects held the manipulandum with a precision grip either at the bottom (as shown), which was covered with slippery satin, or at the top, which was covered with less slippery sandpaper.

EXPERIMENT 1

Method

Subjects. Twenty-five subjects (15 female and 10 male) between 18 and 50 years of age participated in these experiments after giving informed consent. The subjects included members of the subject panel and staff of the MRC Applied Psychology Unit. The 21 panel subjects were paid for their participation.

Apparatus. Subjects gripped a manipulandum (width 4.5 cm) with the tips of the thumb and index finger on either side. The manipulandum was instrumented with a 3-D force transducer (Novatech Model F233) that provided measures of the grip force normal to the surface and the load or pulling force tangential to the surface. The force data were sampled at 200 Hz. The transducer was attached to a servo-controlled linear motor (see Figure 1) that could deliver a controlled force tending to pull the object away from the subject's hand. The subject was required to resist the pull force and to hold the object in a fixed position. The manipulandum could be grasped at one of two locations: one covered in smooth satin and the other covered in rough sandpaper (Figure 1).

This linear motor was mounted, at right angles, on top of a second linear motor that permitted free motion in the lateral (Y) direction. If the subject exerted unequal normal forces on the two sides of the manipulandum, the latter moved laterally. Thus, the instruction to hold the object in a fixed position guarded against the possibility that unequal forces would be applied.

Procedure. Each subject completed four sets of trials. In each set, the subject completed nine trials in which he/she compared the force of a test load with the force of a reference load. The test load varied randomly between 4.25 and 9.75 N, whereas the reference load was always close to 7 N ($M = 6.9$ N; $SD = 1$ N). This range of load forces roughly corresponds to the range of gravitational loads examined in our previous study, based on lifting weights (Flanagan et al., 1995). In all trials, the reference load was followed by the test load. The subject's task was to tell the experimenter whether the test load was stronger or weaker than the preceding reference load. The subject was told that he/she must respond "stronger" or "weaker" and that he/she should not respond that the two pulls were equal. Subjects were not given correct-answer feedback. Each subject was given a few practice trials to make sure that he/she understood the task.

Each trial was initiated by the experimenter once the subject had grasped the object. The pulling force (of the reference load) started to increase 1 sec after the start of the trial, was maintained at a more or less steady level for about 2.5 sec, and then started to decrease 4 sec after the start. This procedure was then repeated for the test pull. The mean ± *SD* of the root-mean square (RMS) error of the load for the period between 2 and 4 sec after the start, averaged across all trials, was .77 ± .91 N. A typical trial is shown in the top panel of Figure 2. Note that no instruction was given to the subject about grip force and thus grip force was "self-selected." As illustrated in the figure, the grip force (thick trace) increased sharply following the onset of the load force (thin trace), was maintained at a more or less steady level, and then dropped back after the offset of the load force. The mean ± *SD* of the RMS error in grip force for the period between 2 and 4 sec was .79 ± .40 N.

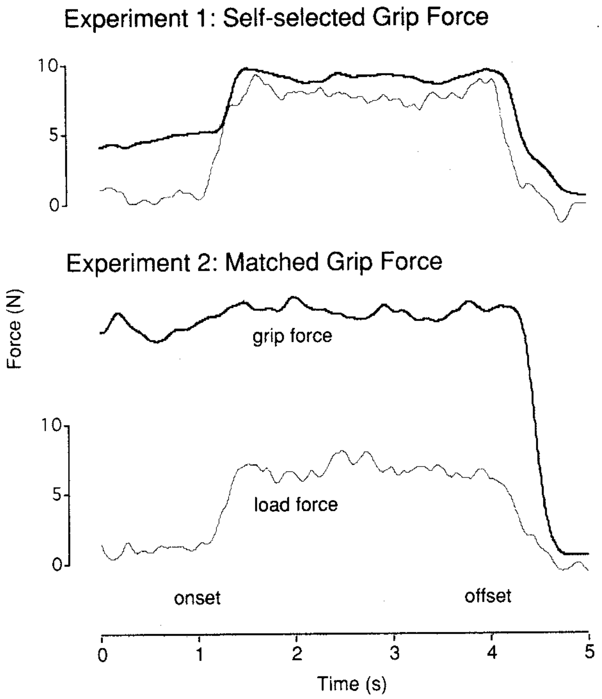

Figure 2. Illustrative grip force (thick traces) and load force (thin traces) records for a trial from Experiment 1 (top) and a trial from Experiment 2 (bottom). In the first experiment, no instructions were given to the subject about grip force. There was a reactive increase in grip force following load onset (at 1 sec) and, thereafter, grip force was scaled for the load force and surface texture of the manipulandum. In the second experiment, subjects were told to increase grip force prior to the trial to a high level and to maintain this force throughout the trial.

In the first two sets of trials, the surface textures for the reference and test pulls were the same. In the "smooth-smooth" trials, the surface texture was smooth for both loads, and in the "rough-rough" trials, the surface texture was rough for both loads. The order in which these two sets were performed was varied across subjects. In the second two sets of trials, the surface textures of the reference and test pulls were different. In "smooth-rough" trials, the surface was smooth for the reference load and rough for the test load, whereas in the "rough-smooth" trials, the surface was rough for the reference load and smooth for the test load. Again, the order in which two sets of trials were performed was varied across subjects.

Analysis. Because of limitations of the servo-controller and interactions between the object and hand, the actual, measured load force was somewhat variable and was not always equal to the specified load force. In order to quantify the difference between the test load and the reference, we subtracted the mean measured reference load from the mean measured test load for each trial. (The means were computed for the period between 2 and 4 sec after the start.) On the basis of these load differences, trials were sorted into nine bins the central values of which ranged from -2.5 to 2.5 N in steps of 0.5 N. (Thus, for example, the middle bin contained values between $-.5$ N and .5 N.) A negative value indicates that the test load was smaller than the reference load. Because of the possibility that subjects may have been particularly sensitive to the maximum load on a given trial (as opposed to the average load), we carried out a similar analysis using the difference between the maximum test load and the maximum reference load. These differences were then sorted into nine bins ranging from -2.5 to 2.5 N.

For each of the four conditions (i.e., smooth-rough, rough-smooth, smooth-smooth, and rough-rough), the frequency of responding "weaker" was determined for each load difference. The probability of responding "weaker," $p(W)$, is simply the ratio of this frequency divided by the total number of observations. The probability was then plotted as a function of the difference between the test and reference load forces. Logit analysis (McCullagh and Nelder, 1989) was used to test for differences in the probability functions between conditions.

Results and Discussion

Panel A in Figure 3 shows $p(W)$ curves for the conditions in which the surface textures for the test and reference loads were either both smooth (open circles, dashed curve) or both rough (filled circles, solid curve). The following logit model was used to obtain estimated $p(W)$ curves as a function of surface texture (T) and the difference in load (Δload):

$$p(W)=\frac{\exp\left(\beta_0+\beta_1 T+\beta_2 \Delta\text{load}\right)}{1+\exp\left(\beta_0+\beta_1 T+\beta_2 \Delta\text{load}\right)}, \qquad (1)$$

where T equals 0 or 1 depending on whether the texture of the test load was smooth or rough. In this model, it is assumed that the $p(W)$ curves for the two texture conditions are of equal steepness but may be shifted, horizontally, with respect to each other. As can be seen, the model provides a good fit to the data ($r = .98$).

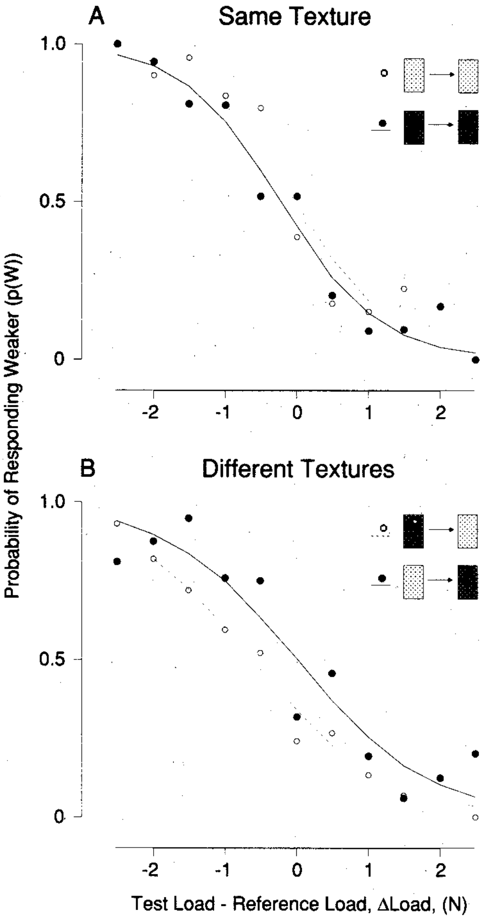

Figure 3. Group ($n = 25$) psychometric functions for weight discrimination judgments when test and reference loads were covered with the same texture (panel A) or different textures (panel B). Curves represent the probability of responding that the test load was weaker than the previous reference load.

When the test load was 2.5 N less than the reference ($\Delta\text{load} = -2.5$ N), $p(W)$ was close to 1. Conversely, when the test load was 2.5 N greater than the reference, $p(W)$ was close to 0. In addition, for both the smooth-smooth and rough-rough conditions, $p(W)$ was close to 0.5 when the difference between the test and reference loads was less than ± .25 N ($\Delta\text{load} = 0$ N). Note that the $p(W)$ curve for the smooth-smooth condition is shifted slightly to the right of the $p(W)$ curve for the rough-rough condition. However, the difference is not large and for any given value of Δload, the probability of responding "weaker" is similar for the two surface textures.

To test whether the shift between $p(W)$ curves was significant, logit regression analysis was employed. The following model was evaluated:

$$\log\left\{\frac{p(W)}{1-p(W)}\right\} = \beta_0 + \beta_1 T + \beta_2 \Delta\text{load}. \qquad (2)$$

This model is a simple transform of Equation 1 and has the effect of linearizing the data. The regression analysis revealed that β_1 was not reliably greater than zero [$t(19) = 1.44, p = .17$], which indicates that the slight shift between the $p(W)$ curves in Figure 2A was not statistically significant. Thus, the probability of judging the test load to be weaker than the reference does not depend on whether the two surface textures are rough or smooth.

The lower panel of Figure 3 shows the $p(W)$ curves obtained for the rough-smooth (reference test) condition (open circles, dashed line) and the smooth-rough condition (filled circles, solid line). In this case, the $p(W)$ curve for the smooth-rough condition is clearly shifted to the right of the $p(W)$ curve for the rough-smooth condition. Thus, for any given difference in load, the probability of judging the text load to be weaker than the reference is greater when the test is rough and the reference is smooth than the other way round. Conversely, the chances of judging the test load to be stronger than the reference is greater when the test is smoother than the reference than when the test is rougher than the reference.

The evaluation of the logit regression model (Equation 2) for these data revealed that β_1 was reliably greater than zero [$t(19) = 2.93, p = .009$]. Thus, the difference between the $p(W)$ curves in the lower panel of Figure 2 is statistically significant. The magnitude of the shift is given by the ratio of β_1 and β_2, which was found to be 0.62 N. In other words, on average, the pulling force for the rough surface had to be 0.62 N greater than the pulling force of the smooth test object for the load to be perceived as the same.

Similar results were obtained when we carried out the analysis using the difference between the maximum load forces of the test and reference pulls (as opposed to the average load forces). Comparison of the rough-rough and smooth-smooth conditions indicated that β_1 was not reliably greater than zero [$t(19) = 1.35, p = .19$]. However, comparison of the rough-smooth and smooth-rough conditions indicated that β_1 was reliable [$t(19) = 3.31$, $p = .004$].

The pattern of results for pulling loads observed in the present experiment corresponds to the results for lifting weights in our previous study (Flanagan et al., 1995). However, in the present study, grip force was recorded. In both cases, surface texture influenced weight discrimination; the smoother the surface texture, the stronger (or heavier) the perceived load (or weight). We would argue that this finding reflects the fact that the grip force needed to prevent the object from slipping is greater when the surface texture is smooth than when it is rough.

To assess the effects of load force and surface texture on grip force, a linear regression analysis was carried out in which the dependent variable was the mean grip force (GF) measured during the test pull, and the two independent variables were the mean load force (LF) during the test pull and the surface texture (T) of the test pull. (Means were computed for the period between 2 and 4 sec after the start of the trial.) Thus, the regression equation was as follows:

$$GF = \beta_0 + \beta_1 T + \beta_2 LF + \beta_3 (T \cdot LF), \qquad (3)$$

where T equals -1 or 1 depending on whether the surface texture of the test load is rough or smooth, respectively. The coefficient β_1 tests for different intercepts between the two textures and the coefficient β_3 tests for different slopes. Data from all four conditions and all subjects were combined.

Both the overall slope of the relation between *GF* and *LF* ($\beta_2 = .68$) and the difference between the slopes for the two textures ($\beta_3 = .15$) were found to be statistically reliable ($p < .001$). The greater slope observed for the smooth texture ($\beta_2 + \beta_3 = .83$) than for the rough texture ($\beta_2 - \beta_3 = .43$) is consistent with previous reports on precision grip force control (Cole & Johansson, 1993; Johansson & Westling, 1984b). The overall intercept ($\beta_0 =$ 4.28 N) was statistically significant ($p < .001$) but the difference between the intercepts ($\beta_1 = .05$) was not ($p > .70$). The mean grip forces measured for the test loads, collapsed across subjects and conditions, were 7.83 N for the rough surface and 9.94 N for the smooth surface. The difference (2.11 N) can be attributed to the difference between the grip load slopes for the two textures. These statistics confirm that grip force was greater for the smooth texture than for rough texture and thus support the hypothesis that "smooth loads" are judged to be stronger than "rough loads" because grip force is greater.

In a previous study (Flanagan et al., 1995), we demonstrated that the weight discrimination is influenced by surface texture when an object is lifted with a precision grip. In the lifting case, the weight represents a gravitational load. The results of Experiment 1 indicate that this phenomenon generalizes to other (nongravitational) loads. Regardless of whether the subject is required to discriminate between weights or pulling loads, when the object is grasped with a precision grip, load perception is influenced by the surface texture of the object. In both cases, the more slippery the surface texture, the greater the perceived load.

EXPERIMENT 2

We have hypothesized that a load covered by a smooth surface texture is judged to be greater than one covered by a rough surface texture because the grip force required to hold it and prevent it from slipping is greater. This hypothesis predicts that if the grip force used to grasp the load is the same for two textures, there should be no effect of surface texture on perceived load. The aim of the second experiment was to directly test this hypothesis.

Method

Subjects. The same 25 subjects who participated in Experiment 1 participated in Experiment 2. All subjects completed the first experiment and then the second.

Apparatus. The apparatus was the same as in the first experiment. However, an oscilloscope was added to provide the subjects with visual feedback of the magnitude of their grip force as well as a target grip force level, which was marked on the oscilloscope. The target grip force (about 19 N) was well above the level required to prevent the manipulandum from slipping even with the smooth (satin) surface texture and the maximum load force. At the same time, the target grip force was well below the maximum possible grip force healthy adults can generate (anywhere from 40 to 90 N).

Procedure. Each subject completed two sets of trials. In each set, the subject had to compare the force of nine test loads with the force of a reference load. As in the first experiment, in each trial a reference load of about 7 N was followed by the test load, which varied randomly between 4.25 and 9.75 N. The subject's task was to indicate whether the test load was stronger or weaker than the preceding reference load.

Prior to the onset of each trial, the subject was required to grasp the manipulandum and to increase his/her grip force to the target level marked on the oscilloscope. The subject was instructed to maintain this grip force throughout the trial. Once the subject had reached the target level, the experimenter initiated the trial. As in the first experiment, the pulling force (of the reference load) started to increase 1 sec after the start of the trial, was maintained at a more or less steady level for about 2.5 sec, and then started to decrease 4 sec after the start. This procedure was then repeated for the test pull.

An illustrative pull from Experiment 2 is shown in the bottom panel of Figure 2. Unlike the self-selected condition (Experiment 1), grip force was elevated at the start and was maintained until the release of load force. In general, subjects successfully maintained a fairly constant grip level in these trials with little or no change in grip force following load force onset.

In one set of trials, the surface textures for the reference and test pulls were smooth and rough, respectively (smooth-rough condition), whereas in the other set, the surface texture of the reference was rough and that of the test smooth (rough-smooth condition). The order in which two sets of trials were performed was varied across subjects.

Analysis. The data were analyzed in the same way as in Experiment 1. That is, trials were sorted into nine bins depending on the difference between the mean load force on the test pull and the mean load force on the test reference pulls (Δload). The nine bins ranged from -2.5 to 2.5 N in steps of 0.5 N. For both the smooth-rough and rough-smooth conditions, the probability of responding "weaker," $p(W)$, was then plotted as a function of Δload. Logit analysis was used to test for differences in the probability functions obtained for the two conditions. Once again, a similar analysis was carried out using the differences between the maximum load forces from the test and reference pulls.

Results and Discussion

To test whether subjects were able to comply with the instruction to maintain a constant, elevated grip force for all trials, a linear regression analysis was carried out to test for possible effects of mean load force and surface texture on mean grip force in the test pulls. Data from all subjects were combined. Neither mean load force nor texture was statistically significant ($p > .10$). Moreover, there was little difference between the mean grip forces of the test pulls, collapsed across trials and subjects, for the rough (18.7 N) and smooth (18.9 N) surfaces. Thus, the subjects successfully matched grip forces across textures.

Figure 4 shows the $p(W)$ curves obtained for the rough-smooth (open circles, dashed line) and smooth-rough conditions (filled circles, solid line). As can be seen in the figure, the two $p(W)$ curves are very similar. This was confirmed using logit regression analysis, which revealed that the shift between the two curves, as reflected by β_1 in Equation 2, was not reliable [$t(19) = 0.32$, $p = .75$]. Thus, when subjects used a constant, elevated grip force while resisting pulling loads, no effect of surface texture on perceived load was observed. A similar result

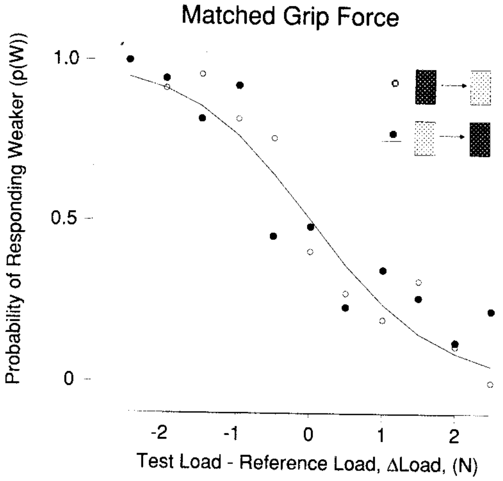

Figure 4. Group ($n = 25$) psychometric functions for weight discrimination judgments when grip forces were matched across surface textures. Curves represent the probability of responding that the test load was weaker than the previous reference load.

was obtained when we carried out a logit analysis based on the difference between the maximum load forces of the test and reference pulls rather than the average load forces. Once again, β_1 was not reliably greater than zero [$t(19) = 0.17, p = .87$].

It is interesting to compare the $p(W)$ curves obtained in Experiment 2 with those obtained in the first experiment. The $p(W)$ curves observed in Experiment 2 are shifted to the right of the $p(W)$ curves obtained for the smooth-smooth, rough-rough, and rough-smooth conditions. Thus, grasping with an elevated grip force seems to involve a greater tendency to judge the second, test load, to be weaker.

In order to directly compare the results of Experiments 1 and 2, we combined the data from the smooth-rough and rough-smooth conditions in the first experiment with the data from the second experiment and tested the following logit model:

$$\log\left\{\frac{p(W)}{1-p(W)}\right\} = \beta_0 + \beta_1 T + \beta_2 G + \beta_3 TG + \beta_4 \Delta\text{load}, \quad (4)$$

where T codes for the surface texture of the test load, G codes for grip condition (self-selected or matched), and TG is the interaction between texture and grip condition. As expected, the analysis revealed that β_3 was reliably greater than zero [$t(39) = 2.31, p = .026$]. In other words, there was a significant interaction between surface texture and grip condition. Whereas there was a clear effect of texture on $p(W)$ in the self-selected grip force condition, the effect was not observed in the matched grip force condition. The analysis also revealed that β_2 was reliably different from zero [$t(39) = 2.43, p = .020$], indicating an overall effect of grip condition. This confirms what was noted above: With an elevated grip force, there is a greater probability of responding that the second, test pull, is weaker.

In summary, the results of Experiment 2 support the hypothesis that the influence of surface texture on weight and load perception, observed under normal conditions, is due to differences in grip force. When grip forces are matched across surface textures, surface texture no longer exerts an influence on perceived load.

GENERAL DISCUSSION

In the two experiments reported in this paper, we have shown that when pulling loads are applied to a manipulandum held with a precision grip (with the thumb and index finger on either side), the perceived load is influenced by grip force. The results of the first experiment demonstrated that when the contact surfaces are slippery satin—requiring a relatively large grip force to prevent slip—the perceived load is greater than when the contact surfaces are sandpaper—requiring a relatively small grip force to prevent slip. The results of the second experiment showed that when an elevated and equivalent grip force was used for the two types of surface texture, there was no effect of texture on perceived load. Taken together, these findings suggest that, under normal conditions, the increased grip force needed to stabilize a more slippery object leads to the perception that the load is greater.

Great care is taken in the psychophysical literature not to confuse physical quantities, and it is important not to assume, a priori, that weight discrimination is synonymous with load discrimination (see, e.g., Ross & Brodie, 1987; see Jones, 1986, for a review of force and weight perception). Although, in physical terms, weight is simply a vertical load force due to gravity, one might expect it to be a special class of load. In our earlier study (Flanagan et al., 1995) we showed that when subjects lift weights held in a precision grip (with the digits at the sides), weight perception is biased by surface texture. We also showed that when the grip was altered so that the thumb was underneath and the index finger on top (so that differences in grip force across textures would not be expected), there was no effect. These results led us to conclude that the effect was not due to texture per se and to suggest that a smooth object will be judged to be heavier than a rough object of the same weight because the grip force required to grasp it is greater. Taken together, the results of the present experiments and the earlier study suggest that weight and horizontal pull loads are similarly affected by surface texture.

The results of Flanagan et al. (1995) and the results of Experiment 1 in the present study can be interpreted either in terms of central (efferent) or peripheral (afferent) mechanisms, or both (see Matthews, 1982, for a discussion of the relative importance of efferent and afferent muscle signals in load perception). According to the central interpretation, one would argue that subjects fail to fully distinguish between the sense of effort associated with grip force and the sense of effort associated with supporting the load, and that the cumulative sense of effort contributes to load perception. This failure to partition the sense of effort might reflect the fact that, due to the complicated configuration of intrinsic and extrinsic hand muscles, there is not a strict division of muscles according to the direction of force. That is, in general hand muscles produce both grip forces and forces resisting the load. Another interpretation of this central effect is that the brain issues a unitary command for stabilizing the object that is subsequently segregated into grip and load components. This unitary command would be different (and perhaps larger on a perceptual scale) when the subject is stabilizing a more slippery object.

It is also possible, however, that the effect is due to sensory factors. In particular, sensory information (from cutaneous receptors or proprioceptors) associated with friction between the skin and contact surface might bias the perception of load. The results of the second experiment would appear to favor a central interpretation. However, we still cannot rule out a peripheral account since, for example, it is possible that sensory cues are diminished with elevated grip forces. (Indeed, this may partly explain why people tend to grasp objects with just slightly more grip force than is strictly necessary to present slip; Flanagan, in press.) Another possible interpretation of our results is that the indentation of the finger tip pulp produced by grip force normal to the contact surface may be indistinguishable from the deformation caused by load force tangential to the surface. In this case, sensory information associated with deformation of the finger tip pulp would be insensitive to the direction of the force.

Although we have shown that grip force affects perceived (i.e., verbally reported) load, the question arises as to whether this perceptual effect translates into action. That is, does the motor system deal with more slippery objects as if they are heavier than less slippery objects? For example, if subjects were trained to move a series of rough-surfaced objects of varying weight with a constant peak acceleration (adjusting the load force in proportion to the weight), would they overshoot the target acceleration when a smooth object is introduced? In other words, would the motor system treat the smooth object as if it were heavier than a rough object of the same weight and specify too great a load force?

Recently, Goodale and colleagues (Goodale & Milner, 1992; Goodale, Milner, Jakobson, & Carey, 1991) have proposed that there are two distinct routes in the visual system that mediate perception and action (see also Jeannerod, Decety, & Michel, 1994). Moreover, these workers have shown that some perceptual illusions do not translate into action. Aglioti, DeSouza, and Goodale (1995) examined a task in which subjects had to reach for target disks surrounded by other disks that were either smaller or larger than the target. The subjects also had to make perceptual judgments about the size of the target disks. Although subjects' perceptual judgments were influenced by the size of the surrounding disks, the maximum opening between the finger tips during the reach was scaled to the actual size of the target disk rather than the perceived size.

A similar dissociation between action and perception has been observed by Gordon, Forssberg, Johansson, and Westling (1991a, 1991b). These authors asked subjects to compare the weights of large and small objects lifted with a precision grip. Regardless of whether information about the size of object was obtained visually (Gordon et al., 1991a) or through haptic exploration (Gordon et al., 1991b), the rate of rise of both grip force and load force during the initial lifting phase was greater for the large object, presumably because subjects expected the large object to be heavier. However, grip force was quickly recalibrated for the actual weight of the object so that during the holding phase following the lift, the grip forces used to grasp large and small objects of equal weight were the same. Thus, even though the subjects perceived the smaller object to be heavier (in line with size–weight predictions), the sensorimotor control mechanisms responsible for updating grip force were not "fooled" by object size.

In summary, we restate the main finding of the experiments reported in this paper. First, we demonstrated that when a pulling load is applied to an object held with a precision grip, the perceived load is greater when the contact surface between the skin and object is more slippery. However, when the grip forces employed to grasp objects of varying slipperiness are equated, there is no effect of texture on perceived load. These results suggest that the grip force used to grasp an object influences the perceived load acting on the object and provide an example where constraints of motor output bias sensory perception.

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