20

Action–Perception Coupling in Judgments of Hand-Held Loads

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1. INTRODUCTION

The hand serves two fundamental functions: manipulation of objects in the environment and perception of object properties such as weight and texture. These two functions are closely coupled. On one hand, objects may be manipulated in specific ways in order to extract various kinds of information about the object (action for perception). On the other hand, information perceived via the hand is critical in coordinating manipulatory actions with objects (perception for action). From the perspective of movement control, an important object property is mass, which will determine both its weight and its resistance to acceleration. With an accurate estimate of the mass of an object, the motor system can appropriately scale the forces needed to hold and move it. Thus, weight or mass judgment is a key area for understanding action–perception coupling.

In this chapter, a series of recent experiments on the effects of surface texture on perceived weight are described. In these studies, surface texture was varied in order to change the grip force required to grasp the object, and the main interest was in the contribution of muscular activity (i.e., activity related to grip force) that is only indirectly involved in supporting the weight.

Hand and Brain

These experiments revealed that when lifting with a precision grip, the smoother the surface texture of the object, the greater the perceived weight. The results suggest that a smoother object is judged to be heavier because the grip force required to prevent it from slipping is greater. The implications of these findings for mechanisms underlying weight perception are discussed. In addition, the effects of surface texture on the perception of weight are compared to the effects of other stimulus properties including object size.

2. MUSCLE ACTIVITY AND SENSE OF FORCE

In his early studies on weight discrimination, Weber (1834/1978) observed that the ability to discriminate weight is better when the weights are actively lifted by the hand than when they are passively supported by the hand. This finding suggests that there is a sense of force, associated with voluntary muscular exertion, which contributes to the perception of weight (Bell, 1834) and many subsequent studies have confirmed the role of muscle activation in weight discrimination (L. A. Jones, 1986). The relative contributions of efferent and afferent muscle signals to this sense of force is still a matter of debate (see Jones, Chapter 17, for a discussion of central and peripheral contributions to force and weight perception). However, a number of investigators have suggested that it is likely that both contribute (e.g., Brodie & Ross, 1984).

It is often implicitly assumed that weight perception depends on the activity of only those muscles directly involved in lifting. However, recent results reported by Kilbreath and Gandevia (1991) suggest that perceived weight is sensitive to muscle forces that do not contribute directly to lifting the weight to be judged. In particular, these authors found that the perceived heaviness of a reference weight lifted by one digit increased if a concurrent weight, equal to or greater than the reference, was lifted at the same time by another digit of the same hand. However, Kilbreath and Gandevia also reported that when the concurrent weight was lifted by the ankle, there was no increase in perceived heaviness. Thus, the effect of a concurrent load appears to depend on whether the muscle forces involved are functionally related in everyday tasks, as is presumably the case for forces produced by one hand. It should be kept in mind, however, that the concurrent lifting task studied by these investigators was a laboratory task; it is possible that in well-practiced, functional tasks, concurrent loads are compensated for, perhaps on the basis of experience.

Kilbreath and Gandevia's (1991) results suggest that the sense of force that contributes to weight perception may be more accurately considered as the sense of functionally related forces. This may have functional implications for weight perception of grasped objects. When lifting an object with the tips of the thumb and the index finger at its sides (precision grip), the fingertips must exert vertical forces (tangential to the surface) to counter the load as well as normal forces (into the surface) that allow the development of frictional forces to prevent the object slipping from grasp (see Wing, Chapter 15; Johansson, Chapter 19). The normal or grip force, which stabilizes the object but does not contribute directly to lifting it, may be viewed as a concurrent load that might influence perceived weight.

3. FINGER TIP FORCES IN PRECISION GRIP

Before describing the forces involved in precision grip, it is important to define the terms force, load (or load force), and weight. The load force is the sum or resultant of all forces acting on an object. When lifting an object, the load force is the sum of the gravitation force and the inertial force, which is equal to the mass of the object multiplied by it acceleration due to movement. The gravitational force is equivalent to the weight of the object and is simply the product of the mass and the acceleration due to gravity. Note that when holding a free object in a stationary position, the load force is equal to the weight.

In order to prevent slip when lifting an object with a vertical precision grip (the thumb and index finger contact surfaces on opposite sides of the object, see Figure 1), the limiting friction (f) between the skin and object must exceed the shear force due to the load force. The limiting friction depends on the product of the coefficient of friction (μ) and the grip force (G) such that $f = \mu G$. Thus, for a given object weight, the more slippery the surface texture (i.e., the smaller the value μ), the greater the grip force required to prevent slip.

When lifting an object of unknown weight with a precision grip, subjects will initially employ a large grip force to ensure that the object does not slip. However, the grip force is subsequently relaxed until slip occurs and then increased a little so that the grip force is slightly above the minimum required to prevent slip (Westling & Johansson, 1984). When the weight and surface texture of the object can be predicted by the subject, grip force adjustments are anticipatory. Both the rate of rise of grip force during the initial loading phase (prior to lift-off) and the steady grip force during the subsequent holding phase are scaled to the expected weight and slipperiness of the object (Johansson & Westling, 1984b). The heavier or more slippery the object, the greater the rate of rise of grip force and the greater the grip force during the subsequent holding phase. Knowledge of these object properties may be based on memory from previous lifts and on visual and haptic cues (A. M. Gordon et al., 1991a, 1991b).

Johansson and Westling (1988a) have demonstrated that if the weight of

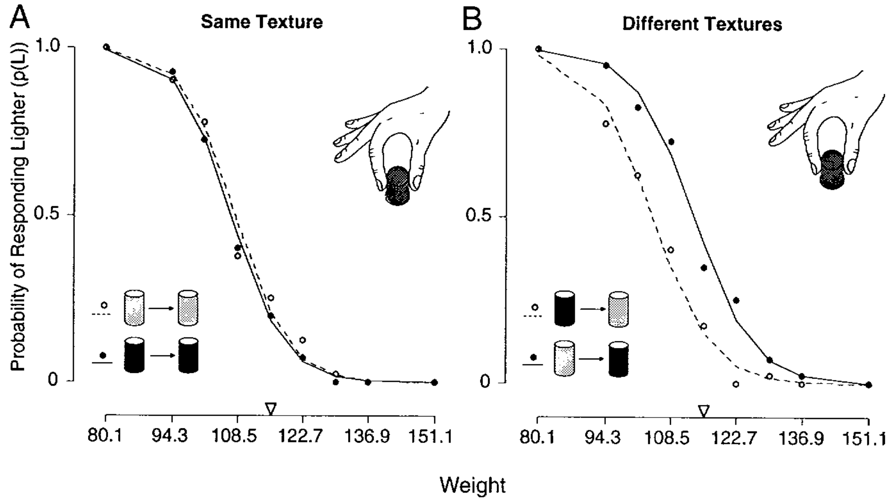

FIGURE 1 Probability (n = 40) of responding that the test canister is lighter than the previously lifted reference canister [p(L)] when test and reference canisters were the same texture (A) or different textures (B). Open circles and dashed lines code the condition in which the test canister was smooth and the solid circles and solid lines code the condition in which the test canister was rough. The triangle indicates the reference weight. (Points at which the probability was the same in both conditions are half open and half closed.) (From Flanagan et al., 1995)

the object is unexpectedly changed after a series of lifts, the initial rate of rise of grip force may be erroneous. However, in this event, secondary adjustments in grip based on sensory feedback are observed immediately after lift-off (if the object is lighter than expected) or around the expected time of lift-off (if the object is heavier than expected). Moreover, in their earlier experiment Johansson and Westling (1984b) showed that changes in surface texture result in early grip force adjustment (within 60–90 ms of initial contact with the object) so that the appropriate level of grip force may already be set by the time the object is lifted off the table surface. (In elderly subjects, however, full adaptation to an unexpected change in surface texture may be prolonged [Cole, 1991]. Even so, by the second or third lift, grip force is fully adapted.) Thus, regardless of whether or not the initially programmed grip force is appropriate, by the time the object is lifted and held aloft, grip force is precisely scaled for the frictional demands imposed by the object's weight and surface slipperiness. Moreover, if the object is moved vertically after having been lifted aloft, grip force is modulated in anticipation of inertial loads induced by the movement (Flanagan et al., 1993; Flanagan & Wing, 1993).

By varying the surface texture of an object it is possible to manipulate grip force independently of the load force exerted by the fingertips when lifting with a precision grip. The aim of the experiments reviewed in this chapter was to determine whether changes in grip force (related to surface texture) influence perceived heaviness (or load) as revealed in a weight discrimination task. In other words, does grip force act as a concurrent load that affects the perception of the load to be judged? Because grip force is scaled to object weight, it might serve as a useful cue for weight discrimination. On the other hand, because grip force is also scaled to slipperiness, discrimination might be confounded if the objects being discriminated have different surface textures and hence require different grip forces.

4. EXPERIMENTS ON WEIGHT AND LOAD DISCRIMINATION

In this chapter, three experiments on weight and load discrimination are discussed. In the first experiment, subjects compared the weights of a test and a reference object after lifting them successively with the digits at the sides. The objects were covered in either the same texture or different textures. In the second experiment, subjects compared the weights of objects held with the thumb underneath and the index finger on top so that changes in grip force were not required for different surface textures. The aim of this experiment was to determine whether the effect of texture on perceived heaviness, observed in the first experiment, was due to differences in grip force or surface texture per se. The third experiment involved a pulling task rather than a lifting task. In this case, subjects performed a load force discrimination task. However, note that weight discrimination can be viewed as load force discrimination where the load is due to gravity. Visual feedback about grip force was provided and subjects were required to use the same grip force for two different surface textures. If the influence of texture on perceived load is due to grip force, then the effect should be eliminated if grip forces are matched. The first two experiments are described in full in Flanagan, Wing, et al. (1995).

4.1. Effects of Texture When Lifting with a Vertical Precision Grip

In the first experiment, 40 subjects compared the weight of a reference object with the weights of a series of test objects. The objects were 35-mm film canisters (30 mm in diameter and 50 mm high) filled with coins. The canisters were covered in either satin or sandpaper to give a smooth or rough surface. For each surface texture there were 9 test canisters ranging from 80.1 to 151.1 g and a reference canister of weight 115.6 g, which was the central value of the test canisters. In a given trial, the subject lifted a reference canister followed by a test canister with the same, preferred hand using a vertical precision grip with the tips of the thumb and index finger at the sides (see illustrations in Figure 1). The subject had to tell the experimenter whether the test canister was lighter or heavier than the reference or equal in weight. However, subjects were encouraged to respond "lighter" or "heavier" if possible.

Each subject first performed two sets of lifts in which the reference and test canisters were the same texture: smooth–smooth and rough–rough (reference–test). They then performed two more sets of lifts in which the surface textures of the reference and test canisters were different: smooth–rough and rough–smooth. The order of the two "same texture" sets was varied across subjects as was the order of the two "different texture" sets. Subjects were free to move the canisters and no time limit was imposed on the lifts. However, most subjects held each canister in a steady position (after the initial lift) for a second or two before replacing it on the bench.

The results of this experiment are shown in Figure 1. (A) shows the probability of responding that the test canister was lighter, p(L), as a function of the weight of the test canister when both canisters were either smooth (open circles, dashed line) or rough (solid circles, solid line). When the lightest test canister (80.1 g) was lifted, all 40 subjects responded that it was lighter than the reference and p(L) was one. Conversely, none of the subjects responded that the heaviest test canister (151.1 g) was lighter than the reference and p(L) was zero. Note that for both surface textures, when the test canister was equal in weight to the reference, p(L) was less than .5. Thus, there was a bias toward responding that the second, test canister was heavier as has been previously reported (Ross, 1964). Note also that there was essentially no difference between the p(L) curves for the two textures.

Figure 1B shows the p(L) curves obtained when the surface textures of the reference and test canisters were different. As can be seen, the p(L) curve found when the reference canister was smooth and the test was rough (solid circles, solid line) is shifted to the right of the p(L) curve found when the reference canister was rough and the test was smooth (open circles, dashed line). Thus, the probability of responding that the test canister was lighter than the reference was less when the test canister was covered in the smooth (more slippery) texture than when it was covered in the rough texture. Logit analysis revealed that the shift between these p(L) curves was highly significant (see Flanagan, Wing et al., 1995, for details). The shift corresponds to a difference in perceived weight of 9.0 g, 2 g greater than the smallest difference between canisters. There was no significant shift when the textures of the canisters were the same.

In Figure 1 the p(L) curves obtained for the smooth–rough and rough–smooth comparisons fall on either side of the p(L) curves obtained for the same texture comparisons. That is, a smooth test canister was more likely to be judged heavier when the reference was rough than when it was smooth and a rough test canister was more likely to be judged lighter when the reference was smooth than when it was rough. This indicates that the effect of texture on perceived weight did not depend on the order in which textures were presented.

In summary, the results of this experiment reveal that, when lifting with a vertical precision grip, weight perception is influenced by surface texture. Objects covered in the more slippery smooth texture are judged to be heavier than objects covered in a less slippery rough texture. This may be due to the fact that the grip force required to hold the smooth object without slip is greater.

4.2. Effects of Texture When Lifting with a Horizontal Precision Grip

The results of the first experiment are consistent with the hypothesis that the effect of texture on perceived weight is due to changes in grip force. However, another possibility is that the effect is due to texture per se. In order to test this alternative explanation, a second experiment was carried out in which subjects were required to use a horizontal precision grip with the distal pad of the thumb supporting the canister from below and the tip of the index finger on top (see illustration in Figure 2B). In this case, differences in grip force across textures may be assumed to be negligible, since the index finger needs to provide little friction to stabilize the object.

As in the first experiment, subjects (n = 14) compared the weights of a series of test canisters to the weight of a reference canister. The same canisters were used; however, only comparisons involving canisters with different textures were made. In this experiment, the subjects held each canister in a stationary position. In each trial, the experimenter first handed the reference canister to the subject and then, after 2–3 seconds, replaced it with the test canister for a further 2–3 seconds. (Subjects were allowed to ask that the trial be repeated if they were uncertain whether the test was lighter or heavier than the reference.) To allow for a direct comparison between the horizontal and vertical grips, this stationary holding procedure was repeated using a vertical precision grip.

The results of this experiment are presented in Figure 2. (A) shows the p(L) curves obtained for rough–smooth (open circles, dashed line) and smooth–rough comparisons (solid circles, solid line) when using a vertical grip. As can be seen, the findings of the first experiment were replicated; a rough test canister compared to a smooth reference was more likely to be judged lighter than a smooth test canister of the same weight compared to a rough reference. Logit analysis revealed that the horizontal shift between these p(L) curves was highly significant. The shift corresponded to a differ-

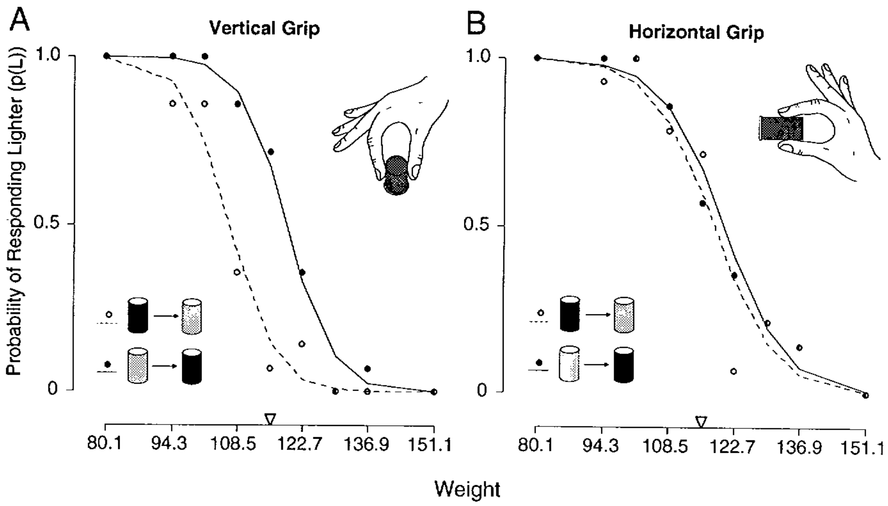

FIGURE 2 Probability ($n = 14$) of responding that the test canister is lighter than the previously lifted reference canister [p(L)] when lifting with a vertical (A) or horizontal (B) precision grip. Open circles and dashed lines code the condition in which the test canister was smooth and the solid circles and solid lines code the condition in which the test canister was rough. The triangle indicates the reference weight. (From Flanagan et al., 1995)

ence in perceived weight of 12.3 g, which is slightly larger than the shift observed in the first experiment.

Figure 2B shows p(L) curves obtained when holding the canisters with a horizontal grip. In this case, there was little difference between the p(L) curves obtained for the smooth–rough and rough–smooth comparisons. Although the p(L) curve for the smooth–rough comparisons was shifted slightly to the right of the curve for the rough–smooth comparisons, the shift was not statistically reliable (see Flanagan, Wing, et al., 1995).

Taken together, the results of the first two experiments suggest that the increase in perceived weight observed when lifting a more slippery object with a vertical grip may be due to the added grip force required to prevent slip and is not due to surface texture per se.

4.3. Effects of Texture When Matching Grip Forces

The hypothesis that grip force, rather than texture, influences perceived weight predicts that if subjects were to employ the same grip force when lifting weights with different surface textures, then texture should not influence perceived heaviness. The objective of the third experiment was to evaluate this prediction. An apparatus was used that measured grip force while generating horizontal loads that subjects were asked to discriminate. Though not strictly weight discrimination, the range of load forces used in this experiment was chosen to correspond to the vertical load forces generated by gravity acting on the masses of the test canisters in the previous experiments. Subjects' ability to discriminate load force in a condition where they themselves selected grip force was compared with their performance in a condition in which they were required to adopt an elevated grip force at the start of the trial.

Twenty-five subjects grasped, with a precision grip, a force transducer attached to a servo-controlled linear motor (see illustrations in Figure 4). The task involved holding the transducer in a fixed position while a pulling force was exerted by the motor. The subject grasped the transducer at one of two locations; one covered in smooth satin and the other covered in rough sandpaper. (The illustrations in Figure 4 show the hand grasping the smooth surface.) The procedure was analogous to that used in the previous experiments. On a given trial, the subject had to indicate verbally whether the force of a test pull was stronger (heavier) or weaker (lighter) than the force of a preceding reference pull. Only comparisons involving different surface textures were examined.

All subjects performed two conditions. In the self-selected condition, which was performed first, no instructions were given about grip force and subjects automatically scaled their grip force for texture and load. In the matching condition, visual feedback about grip force was provided to the subject by means of an oscilloscope. Prior to the onset of the pulling force, the subject was required to increase grip force to a steady high level (marked on the oscilloscope) and to maintain this grip force throughout the pull. The grip force was well above (about 10 N greater) the level employed by the subject when holding the smooth surface in the self-selected condition.

Figure 3 shows grip force (thick line) and load force (thin line) functions obtained for typical trials from one subject in the self-selected and matching conditions. The load force started to increase 1 s after the start of the trial, was maintained at a more-or-less steady level for about 2.5 s, and then started to decrease 4 s after the start. Because of limitations of the servo-controller and interactions between the object and hand, the actual, measured load force fluctuated somewhat both within trials and across trials with the same specified (nominal) load force. In the self-selected trials, grip force increased sharply following load onset. In the matched trials, 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.

The difference between the mean measured test load and the mean measured reference load was computed for each trial. (The means were computed for the period from 2 s after the start to 4 s after the start.) On the basis of these load differences, trials were sorted into 9 bins ranging from −2 to 2 N in steps of 0.5 N. The average load force was 6.8 N.

Figure 4A shows the $p(L)$ curve obtained in the self-selected condition. In general, the probability of judging the test pull to be weaker than the reference was greater when the test was rough and the reference was smooth. Thus, when subjects freely selected grip force when resisting pulling loads, an effect of texture on perceived heaviness can be observed. As in the case of lifting, subjects tended to judge the force to be greater when grasping a smooth object. Logit analysis revealed that the $p(L)$ curve for the smooth–rough condition was shifted to the right of the curve for the rough–smooth condition and that this shift was statistically significant ($t = 2.91$; df = 17; $p < .01$). The shift amounted to a difference of 0.58 N. In other words, on average, the pulling force of the rough test object had to be 0.58 N greater than the pulling force of the smooth test object for the force to be perceived as the same.

Linear regression analysis was used to determine, for the test pulls, the

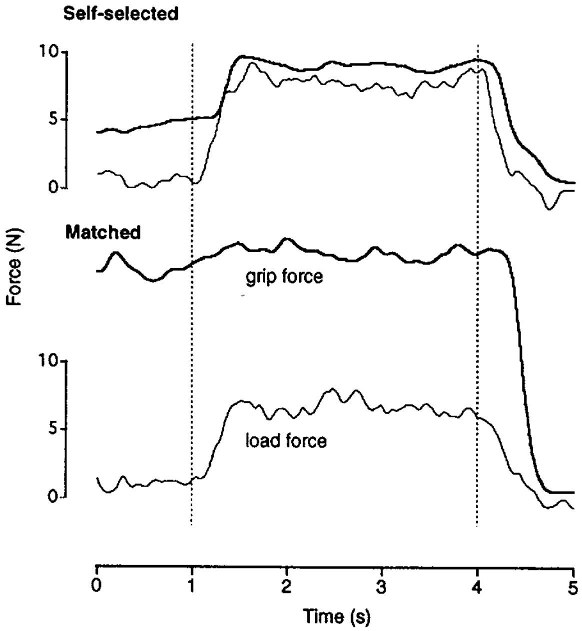

FIGURE 3 Grip force (thick lines) and load force (thin lines) records for a single trial in which grip force was self-selected and a single trial in which grip force was elevated to a target level during the application of the load. The load increased at time = 1 s and decreased at time = 4 s.

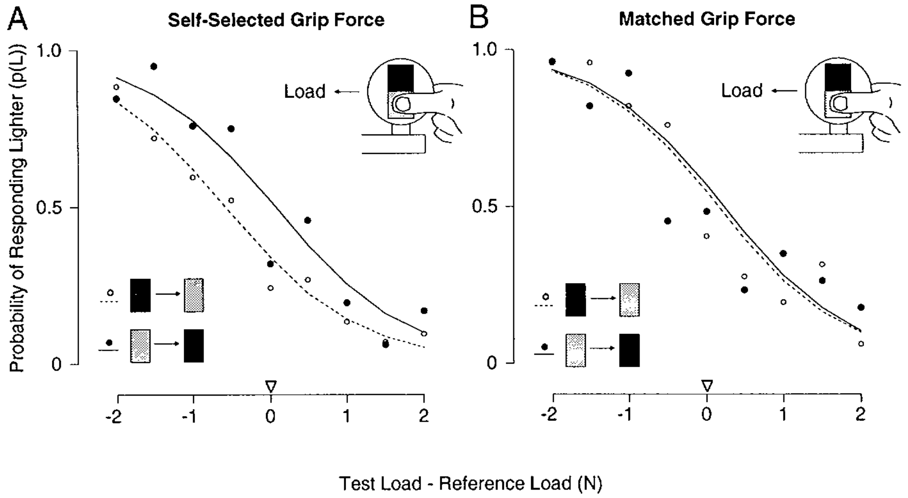

FIGURE 4 Probability ($n = 25$) of responding that the test pull is weaker (lighter) than the previous reference pull [p(L)] when grip force is self-selected (A) or elevated to a constant, high level for both pulls (B). Open circles and dashed lines code the condition in which the surface texture for the test pull was smooth and the solid circles and solid lines code the condition in which the surface texture for the test pull was rough. The triangle indicates the reference weight.

effect of load force, and texture on grip force, while allowing for subject differences in intercept. As expected, the slope of the relation between grip force and load force was significant. The slope was 0.94, indicating an approximately one-to-one correspondence between changes in grip force and changes in load. There was also a reliable difference in the intercept of the best fit relation as a function of texture. On average, for a given load force, grip force was 1.7 N greater for the smooth texture. A similar value was obtained for the average grip forces. The mean grip force, collapsed across subjects and test loads, was 7.9 N for the rough surface and 9.7 N for the smooth surface.

The p(L) curves obtained under the matched grip force condition are shown Figure 4B. In this case, logit analysis revealed that the shift between the two curves was not reliable ($t = 0.346$; df = 17; $p > .05$). Thus, when subjects used a constant, elevated grip force while resisting pulling loads, no effect of texture on perceived heaviness was observed. Analysis of the test pulls revealed that there was little difference between the mean grip forces, collapsed across loads and subjects, for the rough (18.7 N) and smooth (18.9 N) surfaces. Thus, the subjects successfully matched grip forces across textures. The results of this experiment are consistent with the hypothesis that the influence of surface texture on weight and load perception, observed under normal conditions, is due to differences in grip force.

5. SENSE OF MUSCLE FORCE IN WEIGHT PERCEPTION

The results of the three experiments described above demonstrate that when lifting or pulling an object with the tips of the thumb and index finger at its sides, the perceived load depends on the surface texture of the object. In particular, the weight or load of a smooth object will be judged to be greater than that of a rough object of the same weight or load. The results suggest that this effect is due to differences in the grip force required to prevent slip. When lifting with a grasp that does not require appreciable grip force an effect of texture on perceived weight is not observed. In addition, under conditions in which grip force is held constant across textures, there is no effect of texture on perceived load.

The hypothesis that grip force influences perceived heaviness is consistent with the view that a sense of muscle force contributes to weight perception. Moreover, the results suggest that grip force and load force may be lumped together to form an overall sense of force. Thus, the sense of force may be considered more precisely as a sense of functionally related muscle forces. Support for this conclusion comes from the recent work of Kilbreath and Gandevia (1991). As noted earlier, these authors have reported that the perceived weight of a reference load lifted by one digit increases if a concurrent load, equal to or greater than the reference, is lifted by another digit on the same hand.

Consideration of the coefficients of friction between the skin and the surfaces used in the experiments described in this chapter reveals that, even for sandpaper, the normal (grip) force exerted by each digit must be roughly twice the tangential force associated with the load in order to prevent slip (see Flanagan, Wing et al., 1995). Moreover, the mean (self-selected) grip forces observed in the pulling task for both textures were greater than the mean load force. Because the tangential force acting at each digit is one half the total load force, the normal force was more than twice as great as the tangential force. Thus, it is reasonable to suppose that the normal forces exerted when lifting or pulling with a precision grip are large enough to influence force perception.

Although the influence of surface texture on perceived weight would appear, on the basis of the current experiments, to result from differences in grip force, the possible contribution of cutaneous afferents cannot be ruled out. Cutaneous afferents in the tips of the thumb and index finger, which are known to be sensitive to surface texture, may provide information that is used in weight perception. The fact that the effect of texture on weight perception is not observed when using a horizontal grip (Experiment 2) does not preclude the possibility that, when lifting with a vertical grip, cutaneous afferents play a role in weight perception. When lifting with the vertical grip, the situation is quite different from the horizontal case because of frictional forces between the skin and object. It is possible that increased microslips at the digit–object interface when holding a smooth object provide cues for weight perception. Future experiments using anesthesia combined with external feedback of grip force may help resolve this issue. Another approach would be to externally induce small slips (perhaps using vibrations) to test whether these influence weight perception.

Although the results described here are consistent with the view that muscles only indirectly involved in resisting a load can contribute to a sense of force, the relative contributions of central and peripheral signals to this sense of force remains an open issue. Evidence for a central contribution comes from studies showing that perceived weight increases when the central drive or effort required to support a given load is increased by fatigue, partial curarization, or neurological disorders resulting in muscular weakness (see L. A. Jones, 1986, for a review). These observations have led to the suggestion that weight perception is based, at least in part, on the sense of effort associated with central motor commands. However, other studies have provided evidence for a strong afferent contribution to the sense of muscle force. For example, Brodie and Ross (1984) have shown that weight discrimination in reflex lifting (produced by tendon vibration) is significantly better than when passively supporting the object with the hand and is nearly as good as in active lifting. This suggests that receptors sensitive to muscular force contribute to weight perception.

The relative contribution of central and peripheral signals to weight perception may also depend on the precise instructions given to the subject. For example, Roland and Ladegaard-Pedersen (1977) reported that when subjects were told to disregard the increased effort required to generate force following partial curarization of one arm, they could accurately match forces produced by the flexor muscles of the forearms. It would be interesting to test whether the effect of surface texture on perceived weight would persist if subjects were informed about the relation between surface texture and grip force or if they were simply instructed to ignore grip force.

6. COMPARISON OF THE TEXTURE EFFECT WITH THE EFFECTS OF SIZE AND COLOR

The mechanism underlying the effect of texture on perceived weight would appear to be very different from the mechanism underlying the size-weight illusion (Charpentier, 1891) whereby smaller objects are judged to be heavier than larger objects of equal weight. According to the expectancy hypothesis of Ross (1969), the size-weight illusion is subserved by cognitive factors. In particular, Ross suggests that subjects judge the larger object to be lighter because it is lighter than expected and judge the smaller object to be heavier because it is heavier than expected. This can be considered as a cognitive effect because it is based on the subject's knowledge about the properties of real-world objects. A similar effect could operate for surface texture only if texture was correlated with weight in the real world. In other words, if it were the case that slippery objects are typically lighter than rough objects, then subjects might judge a slippery object to be heavier than a rough object of equal weight because the former is heavier than expected. However, there do not seem to be any grounds for supposing that slippery objects are typically lighter than rough objects or that subjects believe this to be the case.

The colors of the two textures used in the experiments described in this chapter were different. Specifically, the smooth satin was light blue and the rough sandpaper was black. De Camp (1917) reported that lighter colored objects are judged to be heavier than darker colored objects. This may reflect the fact that subjects expect the darker colored object to be heavier as suggested by experiments in which weight is judged solely on the basis of visual cues (Bullough, 1907; Payne, 1958). However, it might also reflect a verbal confusion, since the word light refers to both weight and color. One wonders whether the effect would be observed in French speakers, since the French words for weight (*léger*, light; *lourd*, heavy) are different from the words for color (*pâle*, light; *foncé*, dark). It may be noted that the texture effects described in this chapter cannot be explained on the basis of color, since there was no effect when lifting with the horizontal grip.

7. PERCEPTION AND ACTION SYSTEMS

A. M. Gordon et al. (1991a, 1991b) recently examined grip forces in a task in which subjects were required to compare the weights of objects of varying size lifted using a precision grip. (The size of the grip aperture was held constant.) These authors found that the initial rate of rise of grip force during the lift depended on size regardless of whether size information was obtained visually (1991a) or haptically (1991b). The initial rate of rise of grip force was greater for larger objects, presumably because subjects expected the larger object to be heavier. However, grip force was quickly recalibrated for the actual weight of the object so that during the subsequent holding phase the grip forces used to grasp large and small objects of equal weight were the same. Thus, despite the fact that subjects perceived a smaller object to be heavier than a larger object of the same weight (as expected), the sensorimotor control mechanisms responsible for updating grip force are not "fooled" by object size. In other words, while the size-weight illusion appeared to operate at a perceptual level, it did not act at the sensorimotor level.

This distinction between perception and action can be related to the distinction between vision for perception and vision for action advocated by Goodale and Milner (1992; see also Goodale et al., Chapter 2). The question is whether the distinct perception and action routes observed in vision are also observed in other modalities subserved by different neural systems. It would be interesting to see whether the influence of surface texture on perceived weight translates into action. For example, if subjects were trained to move a hand-held object covered in coarse sandpaper with a stereotypical acceleration profile, would they overshoot the target acceleration when the texture is switched to satin? In the case of vision, there is some evidence that the action and perception pathways are at least partly dissociated in visual input. It is not known whether a similar dissociation applies to tactile input.

8. GRIP FORCE AND POSTURAL ADJUSTMENTS

Grip force adjustments during lifting may be conceptualized within a more general postural framework (see Wing, Chapter 15). For example, anticipatory postural adjustments (APAs) involving proximal trunk and leg muscles occur just prior to the initiation of arm movements produced while standing (Friedli, Hallett, & Simon, 1984; Horak, Esselman, Anderson, & Lynch, 1984; W. A. Lee, 1984). APAs generate forces that counteract reactive forces produced by the movement, which, if not compensated for, could destabilize posture (Bouisset & Zattara, 1987; Friedli, Cohen, Hallett, Stanhope, & Simon, 1988). Consider, for example, the task of lifting up a load off a table while standing. Just prior to the lift, the activity of the ankle plantarflexors will increase so as to create a backward torque about the ankles to counteract the forward torque generated by the object's weight. Because the ankle muscle activity is functionally related to the arm muscles involved in lifting, one might predict that the perceived weight of the load will be greater than if the body were supported (e.g., when leaning against the table).

9. CONCLUSION

In this chapter, a set of recent experiments are described showing that the surface texture of an object influences its perceived weight when the object is lifted with the tips of the thumb and index fingers at its sides. The results suggest that a smooth (slippery) object is judged to be heavier than a rough object of the same weight because the grip force required to hold it without slipping is greater. This suggests that subjects fail to distinguish between grip and load force when judging object weight. This hypothesis is consistent with the results of Kilbreath and Gandevia (1991) showing that a concurrent load lifted by one digit leads to an increase in the perceived load lifted by another digit of the same hand. According to these authors, one explanation for this finding is that the central nervous system is unable to partition the destination of motor commands to functionally related muscles and that estimates of heaviness are biased by the total command. Another explanation is that the central nervous system is unable to partition the afferent signals of muscular receptors from functionally related muscles.

The findings reported here stress the close coupling between action and perception in the context of hand function and highlight the dual nature of the hand as manipulator and perceiver of objects in the environment. The findings suggest that the tight linkage between grip and load force observed when lifting (e.g., Johansson & Westling, 1984b; see also Johansson, Chapter 19) and transporting objects (e.g., Flanagan & Tresilian, 1994; Flanagan et al., 1993; Wing, Chapter 15) has perceptual consequences. The information that is obtained about an object during manipulation (e.g., weight) appears to be influenced by constraints acting on action (e.g., texture). Of course, it is also the case that the way in which actors manipulate objects depends on the information they wish to extract. Lederman and Klatzky (1987) have shown that when handling objects, subjects select different grasp strategies (or exploratory procedures) depending on the information (weight, texture, shape, etc.) they are required to obtain (see Lederman and Klatzky, Chapter 21). Thus, the links between action and perception work in both directions.

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