Perception of the Length of Voluntary Movements

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Abstract Two experiments were performed to study the ability of blindfolded subjects to estimate distance on the basis of proprioceptive cues. In the first experiment, subjects judged the length of metal rods that they were allowed to explore freely. With this access to positional as well as other cues, subjects' estimates were a nearly linear function of actual length. These data closely paralleled control measurements obtained under conditions of visual, rather than haptic, inspection.

In the second experiment, each subject slid his or her index finger laterally along a straight path delimited by the apparatus, and then gave a magnitude estimate of the distance through which the finger had moved. Velocity of movement was manipulated by asking subjects, on each trial, to move at one of five speeds ranging from "very slow" to "very fast"; these instructions elicited velocities spanning a 100-to-1 range.

Magnitude estimates of distance in this second experiment increased as a function of actual distance, but decreased as a function of velocity. This latter phenomenon resembles the dependence of perceived distance on velocity that has been shown by other investigators to occur when a stimulus object is drawn across the skin. The data of the present study are consistent with the hypothesis that the perceived length of an active movement depends on a combination of movement and position signals from primary and secondary sensory fibers in muscle spindles.

Movement is an essential part of an animal's interaction with its environment, and the ability to make effective use of sensory information regarding movement is an important aspect of perception. It is therefore surprising that the somesthetic system—broadly defined as encompassing both the cutaneous and proprioceptive senses—often causes the parameters of movement to be *mis*perceived. Study of the mechanisms responsible for such errors of perception may elucidate basic principles of somatosensory coding.

The present paper is concerned with one particular illusion of movement: namely, that the perceived spatial extent of a movement depends not just on its physical extent, but on its velocity as well. Of two movements that differ in speed but are of the same length, the slower will, in many situations, be perceived as extending through a greater distance. This phenomenon has been well studied in the case of movements of a stimulus object along the skin; in this report we examine its occurrence in the

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less well-documented case of active movement of a part of the body—the arm—within a stationary environment. Later in the paper, we show that a straightforward explanation of this kinesthetic form of the illusion, in terms of widely accepted proprioceptive mechanisms, is consistent with our data.

As stated above, however, it is the cutaneous rather than the kinesthetic version of the illusion that has been most thoroughly studied. First reported by Hall and Donaldson (1885), the phenomenon's existence was solidly established by Langford *et al.* (1973). Their apparatus drew the blunt tip of a metal rod along a 12-cm length of skin on the volar forearms of subjects, whose view of the apparatus was blocked. The subjects were then asked to draw the path of the probe on an outline diagram of a forearm. The major result of the study was that subjects drew much longer traverses when the probe had moved slowly than when it had moved rapidly. This trend was accentuated by the tendency for subjects to perceive the probe as following a looping, irregular path when it was moving slowly.

The most extensive study of the illusion using cutaneous stimulation was carried out by Whitsel *et al.* (1986), who explored velocities from 1 to 256 cm/sec along the forearm. While confirming the overall downward trend of perceived traverse length with increasing velocity, they reported that in a narrow, intermediate portion of the velocity range—between about 5 and 20 cm/sec—there was little dependence of perceived length on velocity. Since directional discrimination is optimal over this same velocity range (Dreyer *et al.*, 1978; Essick and Whitsel, 1985), Whitsel *et al.* (1986) suggested that the somatosensory system may be "tuned" for veridical and stable movement perception at these velocities.

The tendency for movements along the skin to seem shorter if they are rapid may be related to a family of perceptual phenomena in which the perceived distance between sequentially stimulated points on the skin depends on the temporal, as well as the spatial, separation between them (e.g., Helson and King, 1931; Lechelt and Borchert, 1977; Lechelt, 1979; Geldard, 1982), although a commonality of mechanism between the continuous and discrete versions of the illusion has never been established.

The focus of the present paper, however, is on movements of a part of the body with respect to the environment, rather than on movements of a stimulus object along the skin. A clear demonstration that the perceived extent of arm movements depends on their velocity was provided by Wapner *et al.* (1967), who asked each of a group of blindfolded subjects to place his or her index finger on a small metal carriage that could be moved laterally by a motor. On a trial, the carriage moved the finger to right or left for a distance of 40 cm. At a point near the middle of the traverse, it passed a marker that was detectable to the subject, and that divided the trial into two portions, within which carriage speed could be set independently. The subject's job was to adjust the position of the marker so that the two parts of the traverse seemed equal in (spatial) length. The major result of the study was that, if the carriage moved more slowly in one portion of the traverse than in the other, subjects tended to shift the marker so as to decrease the extent of the slow-movement portion. In other words, slow movements seemed to extend for a longer distance than did rapid movements of the same size.

In a study resembling that of Wapner *et al.* (1967), but using active rather than passive movement of the arm, Ono (1969) asked blindfolded subjects first to draw a line the length of which was delimited by the apparatus, and then to draw a second line equal in length to the first. The length of the second line was not constrained by the apparatus. On some trials subjects were asked to draw the second line more rapidly, or more slowly, than they had drawn the first line. The result was that subjects drew longer lines when drawing rapidly, suggesting that rapid movements were perceived as spatially shorter than slow movements of the same length.

Ono's results are compatible with those of a more recent investigation (Lederman *et al.*, 1987), in which subjects moved their index fingers at a prescribed speed along a path marked by raised dots, and then estimated the distance traversed. Their responses showed that apparent path length decreased with increasing speed.

The Wapner *et al.* (1967), Ono (1969), and Lederman *et al.* (1987) studies demonstrate that an illusion, similar to that found with movement of a stimulus across the skin, occurs when a part of the body moves through the environment. Although stimulation of cutaneous receptors may have played a role in their results, it was undoubtedly proprioceptive information that made the primary contribution to subjects' perception of limb movement. Their findings thus imply a parallel between some aspect of cutaneous and proprioceptive information processing. However, none of these experiments explored the velocity dimension systematically enough to allow quantitative comparisons with the cutaneous data of Whitsel *et al.* (1986): Wapner *et al.* (1967) used only speeds of 4 and 5 cm/sec; Ono's instructions to his subjects elicited from them rates of movement that covered less than a 3:1 range; and Lederman *et al.* (1987) pretrained their subjects to move at only three speeds.

The purpose of the present study was to explore the effect of velocity on the perceived extent of active movement, in a parametric way, so that (1) the proprioceptive version of the speed–distance illusion could be compared with the extensive data on the cutaneous version of the illusion that are already in the literature; and (2) a beginning could be made toward analyzing the mechanisms underlying the illusion. In accordance with this second goal, a quantitative theory is presented in the "Discussion" section that accounts for the major features of the data and is in accordance with known physiological mechanisms of kinesthesia.

The study consisted of two experiments. In the preliminary experiment, subjects estimated the length of aluminum rods that they were allowed to examine freely by touch. These data provided a baseline with which to compare the length estimates obtained in the main experiment, in which subjects judged the extent of their own movements.

METHODS

SUBJECTS

The subjects were two males (ourselves) and four females (undergraduate students paid for their participation). The latter subjects were naive as to the purpose of the experiments, and did not see the finger movement apparatus until the conclusion of the study. Each subject served in both experiments. A blindfold made from safety goggles covered with adhesive-backed velour and electrician's tape was worn in both experiments, except for those parts of the preliminary experiment that required visual examination of stimuli. The flanges of the blindfold pressed against the skin of a subject's face all around, to block out peripheral as well as central vision.

PRELIMINARY EXPERIMENT

APPARATUS

The aluminum rods used as stimuli in this experiment were 1.3 cm in diameter. They were lightly sanded to eliminate identifying marks, either visible or tangible. A practice set consisted of four rods, with lengths of 2.7, 12.9, 30.9, and 58.4 cm; the test set contained seven rods, with lengths of 1.5, 3.7, 8.8, 15.1, 24.9, 42.7, and 65.7 cm. We used lengths that were not evenly spaced on either a linear or a logarithmic scale, in order to prevent subjects from detecting such regularities and relying on them in formulating their responses.

PROCEDURE

The subject and experimenter sat opposite each other at a table, covered with felt to reduce auditory cues when the rods were placed on it. The subject was told that he or she would be presented wtih rods, one at a time, and was to estimate the length of each. A free-magnitude estimation procedure was used, in that no standard stimulus was provided, and the subject was not told to use any particular units or range of numbers. Subjects were simply told to respond with numbers that were proportional to the lengths of the rods, using a consistent scale throughout the experiment.

On some blocks of trials, subjects wore the blindfold and examined the presented rods haptically, using one or both hands; on other blocks of trials (specified by the experimenter), they removed the blindfold and viewed the presented rods without touching them. In this way it was possible to compare the results of haptic and visual length estimation.

After the procedure had been explained, the experiment began with a practice period designed to familiarize subjects with the task. This consisted of a block of four visual trials, on which the rods of the practice set were presented in random order, followed by a block of four haptic trials, on which the same rods were presented in a new random order. Following this practice period, the set of test rods was presented in a series of eight blocks, with visual and haptic blocks occurring in counterbalanced order (VHHVHVVH for half the subjects, HVVHVHHV for the other half). Within each block, the seven test rods were presented once each in random order.

All rods except the one currently being presented were kept below the level of the table on the experimenter's side, out of view of the subject.

MAIN EXPERIMENT

APPARATUS

In this experiment, active movements on the part of the subject were guided and constrained by a modified slide rule. The frame of the slide rule was firmly attached to the table, and each subject executed movements by placing the terminal phalanx of the right hand's index finger into a depression in the top of a balsa wood rider that was cemented to the cursor. Movements were made by sliding the balsa–cursor assembly laterally along the slide rule. Soap was applied to the top of the slide rule so that the cursor would move smoothly along it with minimal friction.

Subjects always moved the cursor from left to right. Movements began with the cursor positioned at the left end of the apparatus, in contact with a microswitch that was mounted on the frame of the slide rule. A second microswitch, mounted on the right end of the central sliding bar of the slide rule, served as a stop to the movement and allowed the time at which the movement ended to be recorded. Signals from the two microswitches were used to operate a Hunter Klockounter (Model 120C), which recorded to the nearest millisecond the duration of the movement. The experimenter determined the length of a movement in advance by moving the sliding bar, with its attached stop, to one of three marked positions and locking it in place.

PROCEDURE

After a break that followed completion of the preliminary experiment, each subject was brought to the table on which the apparatus for the main experiment was mounted. The apparatus was covered with heavy black felt that concealed its dimensions. The subject was seated facing the table, and donned the blindfold, after which the apparatus was uncovered. To limit contact with the apparatus to the subject's right index finger, he or she wore a sock on the right hand, with a hole in it through which the index finger extended, and was told to keep the other fingers flexed. The subject's left hand remained in his or her lap.

The subject's right hand was guided by the experimenter until the tip of the index finger came to rest in the balsa carriage on the cursor. The subject was then instructed to move the hand to the right, in a single smooth movement, until the resistance of the stop was encountered. Subjects were told that the path on a given trial would be approximately from left to right, but that on some trials it might curve or loop out of a straight line.

A given movement was to be carried out at one of five velocities, described as "very slow," "slow," "medium or normal speed," "fast," and "very fast." At the beginning of each trial, several seconds before giving the subject the signal to begin the movement, the experimenter specified the velocity to be used on that trial.

The subject was told to remove his or her finger from the apparatus as soon as the movement ended, and then to state the length of the path along which the finger had moved, using the same scale of length that he or she had employed in the preliminary experiment. The subject was then asked whether the path had seemed straight or curved. If he or she answered "straight," that ended the trial; however, if it had seemed curved, then the subject was asked to make another magnitude estimate, this time of the straight-line distance from the starting point to the end point of the movement.

A block of trials consisted of 15 movements, one for each combination of the three distances (4, 10, and 16 cm) and five velocity instructions. These 15 trials were arranged in random order, which was different for every block and subject. The experiment as a whole consisted of one practice block and six test blocks. As in the preliminary experiment, responses from the practice block were not included in the data set. Subjects were given a short break (without being allowed to see the apparatus) midway through the experiment.

RESULTS

PRELIMINARY EXPERIMENT

Subjects' magnitude estimates of the length of the aluminum rods were very nearly proportional to their actual lengths, whether the rods were inspected visually or haptically. Figure 1 shows the group data, each point being the geometric mean of all the estimates made of a particular test rod, using a particular method of inspection (visual or haptic). The data of each individual subject were quite consistent with these group functions.

Both sets of data are well fit by power functions. Confirming earlier reports, visual estimates of length are described by a power function with an exponent approximating unity (Stevens, 1961); our data show that this is also true for length estimates based on haptic inspection. Specifically, the power functions that best fit the present data, as determined by the method of least squares, have exponents of 1.00 (visual condition) and 1.02 (haptic condition).

Although the subjects were not specifically instructed to use any established scale of measurement, several of them reported at the end of the preliminary experiment that they had attempted to give their responses in terms of inches. Inspection of Figure 1 suggests that this was indeed the case.

Subjects were quite consistent in the way they carried out their haptic inspection of the rods. They generally began by picking up the rod with one or both hands and

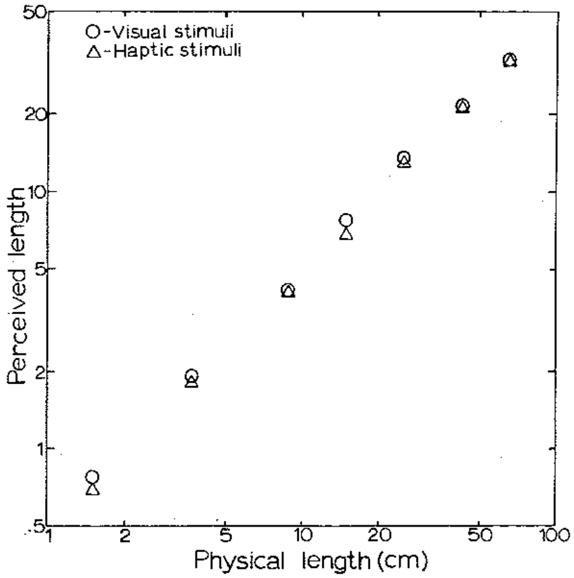

FIGURE 1. Results of the preliminary experiment. Each point is the geometric mean of 24 magnitude estimates (4 from each of the 6 subjects). In this and all subsequent figures, the axes are scaled logarithmically.

sliding their hands along it to the ends. There usually followed a period of several seconds during which the subject held the rod relatively stationary between the two hands, with the palm or fingers of the left hand pressed against the left end of the rod, and the right hand pressed against the right end. The shortest rods were sometimes held between the thumb and index finger of the same hand, rather than between the hands. At the end of this period of stationary inspection, the subject emitted his or her response. Observation of the subjects while they carried out the task gave the clear impression that they relied primarily on proprioceptive position cues, rather than movement cues, in formulating their judgments.

In summary, the preliminary experiment showed that subjects were able to give very accurate estimates of length when permitted to examine the stimuli freely. These data thus established a standard of psychophysical performance against which the judgments made in the main experiment could be evaluated. If length estimates from the main experiment were less veridical, this could be attributed with confidence to a difference in the types of proprioceptive signals available to the subject in the two experiments, rather than to a generalized inability to estimate length accurately by touch.

MAIN EXPERIMENT

Unlike the cutaneous situation in which a stimulus, drawn very slowly across the skin, seems to follow a meandering course (Langford *et al.*, 1973), the active arm movements produced in this study were seldom perceived by the subjects as deviating from a straight path. On only 6.9% of the trials did subjects report that the path of the finger was curved rather than straight, and even on those trials, their estimate of the straight-line distance from beginning to end of the path was only moderately less than their estimate of the length of the path itself. The following data analysis is therefore confined to subjects' estimates of path length.

PERCEIVED LENGTH OF THE 4-CM PATH

The data obtained with the 4-cm path are considered first, because this condition most closely parallels the conditions used by Whitsel *et al.* (1986) in their study of the cutaneous form of the speed–distance illusion. All of the measurements made at this path length in the present experiment are shown in Figure 2, where each point represents a single magnitude estimate, plotted above an abscissa value indicating the velocity of the movement carried out on that trial. Data sets for the six subjects (plotted using different symbols) have been shifted vertically with respect to one another for maximum overlap.

As had been anticipated, subjects were not able to produce five discrete velocities of movement in response to the five velocity instructions, which ranged from "very slow" to "very fast." Instead, velocities were widely and fairly evenly distributed over a 2-log-unit range, from 0.5 to 50 cm/sec.

The data show a clear overall tendency for perceived traverse length to decrease as velocity increases. The data thus confirm and extend the conclusion of Ono (1969) that slow movements of the arm are perceived as extending through a longer distance

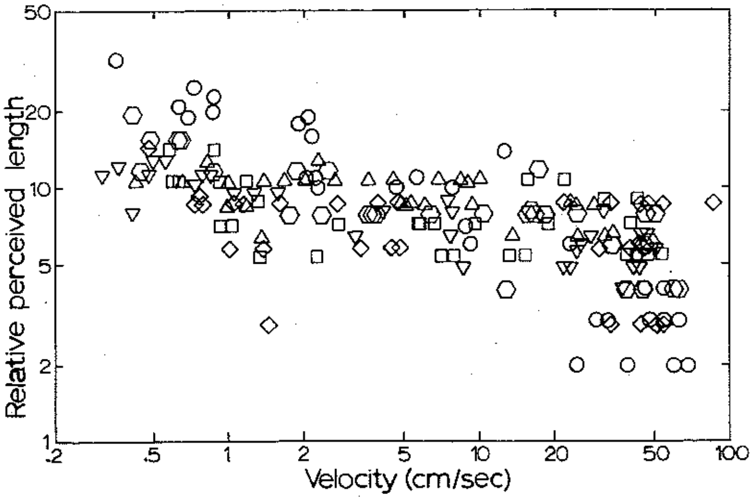

FIGURE 2. Relative magnitude estimates of the length of a 4-cm movement in the main experiment. Each point represents a single judgment. Data sets for individual subjects (plotted with different symbols) have been shifted vertically for maximum overlap with one another.

than rapid ones. This trend was shown by five of the six subjects; the sixth showed no clear effect of velocity on perceived length with the 4-cm traverse (although a trend in the expected direction was apparent in her data at longer traverses).

To facilitate comparison of these measurements on kinesthetic perception with earlier data on the perception of movement of an object across the skin (Whitsel *et al.*, 1986), the present data were combined across subjects into a single function. Since movements did not occur with exactly the same velocities in different subjects, it was necessary to partition the data on the basis of velocity. Accordingly, the velocity dimension was segmented into a series of bins, each 0.2 log unit wide. Within each bin, magnitude estimates were combined across subjects by taking the geometric mean of each subject's estimate, for those subjects who had a data point within that bin. If a subject had two or more data points within a particular bin, the geometric mean of these was computed first, and then this single value was combined with those of the other subjects.

The resulting group function is shown by the circles in Figure 3. The decline in perceived length with increasing velocity, seen in the individual data shown in Figure 2, is also evident here: Perceived length changed by a factor of about three over the velocity ranges obtained in this part of the study.

The curve shown in the figure is replotted from Figure 4 of Whitsel *et al.* (1986). It represents group data in a magnitude estimation task in which subjects assessed the path length of a brush moving along the skin of the forearm. To allow the closest possible comparison, the curve has been slid vertically for maximum overlap with the points—a procedure that does not change its shape, since the ordinate is logarithmic. Although this cutaneous movement function is somewhat steeper than that represented by the data of the present study, the cutaneous and kinesthetic versions of the phenomenon are clearly of the same order of magnitude. Even the plateau in the neighborhood of 10 cm/sec in the Whitsel *et al.* function is paralleled by a similar flat

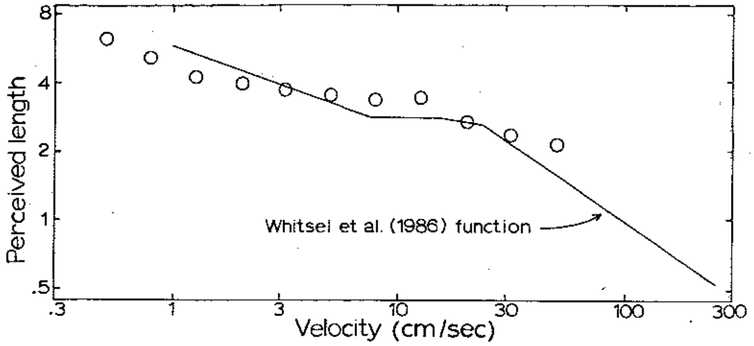

FIGURE 3. Mean extent of the kinesthetic speed–distance illusion for the 4-cm path is shown by the circles, which were obtained by partitioning and combining the data of Figure 2, as described in the text. Data on the cutaneous version of the illusion, replotted from Figure 4 of Whitsel *et al.* (1986), are shown for comparison (solid line).

region in the kinesthetic data, although this was not consistently evident in the data of the individual subjects in the present study.

PERCEIVED LENGTH OF 10- AND 16-CM PATHS

The data of one subject, for all three path lengths, are illustrated in Figure 4. Because we argue in the "Discussion" that the kinesthetic speed–distance illusion involves temporal integration, we have found it useful to plot duration of movement, rather than velocity, on the abscissae of this and the following figure.

The graph shows that perceived traverse length increased gradually, as a function of velocity, at all three path lengths. It was not simply duration of a movement that determined perceived path length, however, for at a given duration the 16-cm path was typically perceived as longest, and the 4-cm path as shortest. While this subject showed about the same magnitude of effect at all three traverse lengths, some subjects showed a more pronounced effect at one length than at another, and some subjects showed no effect at one or another of the path lengths. Every subject, however, showed a clear effect in the expected direction for at least one path length, and no subject ever showed a trend in the opposite direction.

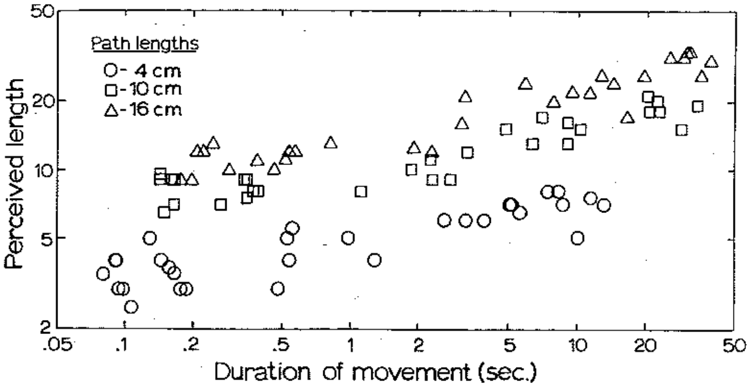

FIGURE 4. Data for a representative subject show that the perceived spatial extent of a movement varies as a function of both its duration and its length. Each point represents a single magnitude estimate of either the 4-cm (circles), 10-cm (squares), or 16-cm path (triangles).

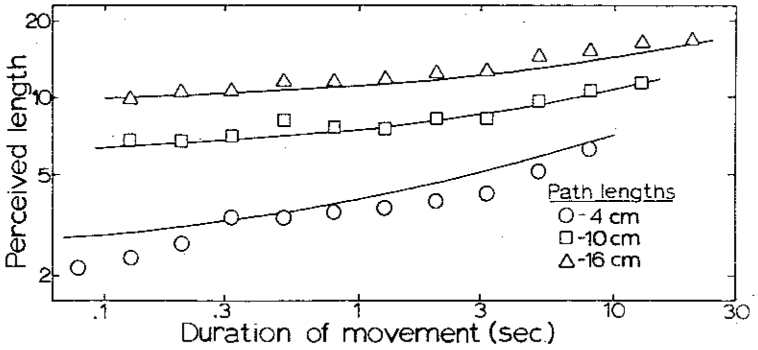

FIGURE 5. Mean perceived length of the 4-, 10-, and 16-cm paths as a function of movement duration. Data were combined across subjects by the method described in the text. The smooth curves represent the theoretical equation proposed in the "Discussion" section: $P = aL^m + bT^n$, where L is distance in centimeters, T is time in seconds, $a = 0.55$, $b = 1.75$, $m = 1.02$, and $n = 0.45$.

The symbols in Figure 5 show the group data at all path lengths, combined across subjects in the way already described for the 4-cm path. The circles, representing this path length, are replotted (this time as a function of movement duration) from Figure 3; the squares and triangles represent data obtained with the 10- and 16-cm paths, respectively. The three sets of data show a similar upward trend as duration increases, although the circles rise somewhat more steeply than the points representing the longer paths.

In summary, then, the kinesthetic form of the speed–distance illusion is a robust phenomenon, obtained across a wide range of velocities and with different path lengths. The increase in perceived traverse length with increasing movement duration is a gradual and orderly one, which invites quantitative modeling. A physiological hypothesis is offered below that attempts to account, quantitatively, for this dependence of perceived length on the duration as well as the actual length of an active movement.

DISCUSSION

The data presented above show that there is, in the kinesthetic domain, an illusion of spatial extent closely analogous to that which has previously been documented for cutaneous perception. How is this kinesthetic effect to be explained? We believe that it follows in a straightforward way from a simple and physiologically plausible hypothesis as to how distance is estimated from kinesthetic information. This hypothesis is now presented.

A THEORY OF KINESTHETICALLY PERCEIVED DISTANCE

Although the cutaneous sensory channels, and signals from joint receptors, are acknowledged to play a subsidiary role in kinesthesia (Ferrell *et al.*, 1987), it is now well established that sensory endings in muscles are the main contributors to a sense of movement of the parts of the body (McCloskey, 1978; Clark and Horch, 1986).

The two main types of receptors in muscle are the primary (group Ia) and secondary (group II) sensory fibers in muscle spindles. These endings are not only anatomically but also physiologically distinct, responding in characteristic ways to muscle stretch (Crowe and Matthews, 1964). The secondary endings produce a signal that is closely related to the length of the muscle, whereas the response of the primary endings varies with both the length of the muscle and the rapidity of stretch. Furthermore, it is well established that proprioception involves both an appreciation of movement and an awareness of position—components that in some situations can be experimentally dissociated (McCloskey, 1973; Clark *et al.*, 1986)—and there is a growing body of evidence to suggest that feelings of movement arise mainly from primary endings, while position sense is due mainly to secondary endings (Clark and Horch, 1986).

The hypothesis offered here builds on this emerging consensus, by suggesting that both types of sensory fibers in muscle spindles contribute to perception of the length of voluntary movements. Signals from the secondary endings, which respond in a static way to muscle length and hence to limb position, can make a highly accurate and unambiguous contribution, for the difference between the firing rate of these fibers before and after a movement is closely related to the extent of the movement. Responses of the primary endings are also rich in information concerning muscle stretch, but in their case the information is ambiguous. The only parameter of movement that can be determined with certainty from their firing pattern is the *duration* of movement. Yet this can be a valuable indicator of the extent of a voluntary movement, for such movements are normally carried out within a narrow and stable range of preferred velocities (Paillard and Brouchon, 1974; Lamb, 1983). This range varies with the nature of the movement and is somewhat different in different individuals, but for a particular person and experimental situation, there is a clear and consistently employed preferred velocity. Given this consistency in the speed of voluntary movement, central processing mechanisms in kinesthesia can obtain a reliable estimate of the extent of such movements simply by registering their duration, as indicated by the period of increased firing of the phasic, primary endings in muscle spindles.

We propose, then, that the perception of the spatial extent of a voluntary movement is a combination—specifically, a weighted sum—of signals from secondary endings that accurately reflect muscle length, and information derived from primary endings that indicates the duration of the movement. This latter contribution will be a reasonably accurate one if the movement has been carried out with the velocity at which it is usually or preferentially executed, but will otherwise be inaccurate: It will cause the extent of slow movements to be overestimated, and that of fast movements to be underestimated.

Our hypothesis is formalized in the equation $P = aL^m + bT^n$, where P represents the perceived length of a voluntary movement, L represents its physical length, and T represents its duration. L and T are each raised to a power, representing the psychophysical transformation that is a general property of sensory channels (Stevens, 1961; Gescheider, 1985). The coefficients a and b represent the weighting factors that reflect the relative importance assigned by central perceptual mechanisms to information obtained from the secondary and primary muscle spindle endings, respectively.

To derive numerical values from this equation, we set m equal to 1.02—the exponent of the power function found to describe the magnitude estimations of rod length obtained in the preliminary experiment—on the assumption that those judgments, involving static and highly accurate appraisal of the stimuli by the subjects, were based primarily on position signals. Values of n, a, and b were chosen for best fit to the movement data obtained in the main experiment. The resulting functions are shown as smooth curves in Figure 5. Although they by no means provide a perfect fit to the measurements, the curves do conform to the major properties of the empirical data set.

Despite this compatibility between theory and data, it should be emphasized that the simple hypothesis presented here represents only a first step toward accounting, in mechanistic terms, for the perceived length of voluntary movements. A more detailed analysis—one that takes into account gamma efferent biasing of muscle spindles, as well as signals from tendon, joint, and cutaneous afferents—would give a more complete picture, but the measurements needed for such an analysis lie beyond the scope of the present investigation. A strength of the hypothesis in its present form, however, is that it allows clear-cut predictions to be made regarding the perception of length under conditions of experimental dissociation of the movement and position components of proprioception. Preparations for such a test of the model are now under way in our laboratory.

RELATION TO OTHER PERCEPTUAL PHENOMENA

The present study has established that the perceived length of voluntary movements depends in a systematic way on the velocity of the movements as well as on their physical length. An operationally different kinesthetic illusion, which may depend on the same principle, is that when contours in a horizontal plane are haptically examined, those that extend "radially" (directly away from the body) feel longer than others of the same size that are oriented "tangentially" (Reid, 1954; Davidon and Cheng, 1964). Wong (1977) showed that subjects moved their arms more slowly in examining radially oriented stimuli than in examining tangential ones, and hypothesized that speed of movement is the underlying cause of the radial–tangential illusion. Since Wong made no measurements of the effect of speed that were not confounded with orientation, however, it is not possible to determine on the basis of his data whether speed alone can account for this illusion.

A further unresolved question is whether the theory we have offered to account for the perceived length of voluntary movements can apply also in the case of passive movements of a limb. Since muscle spindles are involved in detecting both active and passive movements, it would seem that the hypothesis may be equally applicable in both situations. However, the available data regarding the perceived length of passive movements (Wapner *et al.*, 1967) are not extensive enough to allow this possibility to be evaluated.

It is also unknown whether the cutaneous version of the illusion (Langford *et al.*, 1973; Whitsel *et al.*, 1986), in which a stimulus object moves across the skin, can be accounted for in terms of such a two-factor theory. There are, of course, multiple classes of both tonic and phasic mechanoreceptors in the skin, from which central integrators could derive signals reflecting the beginning and end points of a movement, as well as its duration. Moreover, the moderate velocity of voluntary movement at which kinesthetic judgments are especially accurate (Paillard and Brouchon, 1974) seems to have a parallel in the range of velocities of stimulus movement across the skin at which directional discrimination is optimal (Dreyer *et al.*, 1978; Essick and Whitsel, 1985). Thus in some situations somesthetic perceptual mechanisms may interpret sensory information in a way that is appropriate for a particular rate of stimulus movement, even if the stimulus is actually moving at a different rate. The perception of cutaneous movement is extremely complex, however, and it may be that more than a single factor is involved in the velocity–distance illusion on the skin (Whitsel *et al.*, 1986).

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