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Journal of Experimental Psychology:
Human Perception and Performance
1987, Vol. 13, No. 2, 155–177

0096-1523/87/$00.75

Kinematic Form and Scaling: Further Investigations on the Visual Perception of Lifted Weight

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Observers are able to judge accurately the weight lifted by another person when only the motions of reflective patches attached to the lifter's major limb joints and head can be seen (Runeson & Frykholm, 1981). What properties of these complex kinematic patterns allow judgments of weight to be made? The pattern of variation in velocity of the lifted object over position is explored as a source of information for weight: It is found to provide limited information. How are variations in kinematic patterns scaled to allow judgments of weight, a kinetic quantity? The possibility of a source of information for scaling in the kinematics is investigated. Judgments based only on patch–light displays are accurate to a degree that is improved by an extrinsic scaling basis. Finally, the sensitivity to scaling of alternative metrics used in judging is explored. Intrinsic metrics are discovered to be less sensitive to the absence of an extrinsic basis for scaling.

Observers are able to judge with good accuracy the amount of weight being lifted by another person when only the motions of reflective patches attached to the lifter's major limb joints and head can be seen (Runeson & Frykholm, 1981). How is this possible? Runeson and Frykholm (1981, 1983) suggest that unique patterns of motion result from mechanical constraints on the lifter's activity. They have formulated a principle called KSD, or kinematic specification of dynamics, which states that kinematic patterns specify to observers variations in the values of dynamic factors. Further, Runeson and Frykholm (1983) propose that the informative value of kinematic properties of human motion is ensured by design properties of the action system. They review evidence for an emerging understanding of action systems as taking advantage of physical circumstances in the interests of efficiency of both control and metabolic energy consumption. The evidence suggests that control is effected through relatively discrete changes in dynamic properties of the actuators such as stiffness or impedence (Bizzi, 1980; Bizzi, Chapple, & Hogan, 1982; Cooke, 1980; Greene, 1982; Hogan, 1982; Kelso & Holt, 1980; Kelso, Holt, Kugler, & Turvey, 1980; Stein, 1982). If control architecture is coordinated with and parasitic upon the dynamics of the motor and skeletal anatomy, then factors that modulate the dynamics generating a motion may be specified in the motion that results. This, in brief, is the KSD thesis regarding perception of human activity.

KSD is a principle that acknowledges the existence of a hitherto unrecognized class of perceptual properties, namely dynamic factors. For research, the principle simultaneously delineates a new class of perceptual capacity to be explored for particular instances and provides a strategy for finding theoretical accounts in specific cases. The strategy is to investigate the relation between kinematic patterns and dynamical organization in an event, on the one hand, and to investigate the relation between kinematic pattern and perceptual ability on the other. Given evidence that a particular dynamic property of some event is apprehended by observers, a problem is to discover the kinematic properties specifying its presence. Only if we know these can we work backward to an understanding of the constraining dynamics and, thence, to the scaling relation between kinematic properties and the dynamic factor. In Runeson and Frykholm's (1981) experiment, lifters lifted a box from the floor to waist level. Runeson and Frykholm (1983) describe three kinematic properties that might enable observers to judge lifted weight. The first two involve leans performed to preserve balance during the lift. A third kinematic property involves the trajectory of the lifted object. Runeson and Frykholm (1983) point out that the speed at which the box is lifted can be varied and that a lifter may attempt to make the box look heavier by

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These experiments were included in a doctoral dissertation submitted at the University of Connecticut, Storrs, Connecticut. The research was supported by a Fulbright-Hays Pre-doctoral Full Grant for Study Abroad and a University of Connecticut Pre-doctoral Fellowship awarded to the author, as well as a Swedish Council for Research in the Humanities and Social Sciences (HSFR) award to Sverker Runeson. The writing was supported in part by a National Institutes of Health Individual Fellowship Award (AM-07412). Research was performed both at the University of Connecticut and at the University of Uppsala, Uppsala, Sweden.

Heartfelt thanks go to Sverker Runeson, whose work and ideas inspired the present effort. I gratefully acknowledge the help and advice of Sverker Runeson, Bill Mace, Bob Shaw, Michael Turvey, Carol Fowler, Len Katz, and Dave Miller, as well as the constructive criticism provided by Jim Cutting and two anonymous reviewers. Thanks also to Lars-Erik Larsson, Gunnar Agren, and Lars Beckstrom for providing invaluable technical assistance. I also am grateful to the faculty and students at the Department of Psychology in Uppsala and to the staff at the Swedish Fulbright Commission for making my tenure at Uppsala an extraordinarily pleasant and enriching experience. It was a privilege to participate in the tradition of research in event perception initiated by Gunnar Johansson and carried on by Sverker Runeson. I shall long benefit from the opportunity.

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lifting it more slowly. Because this aspect of a lift seems to be under volitional control, it fails to meet the criteria guaranteeing KSD for human action and thus, according to Runeson and Frykholm, can not be counted among informative kinematic properties. Their study of deceptive intention showed that observers were able to see through the attempts at deception and to detect with fair accuracy both the actual weight of the box lifted and what the weight was supposed to be according to the deception. Runeson and Frykholm suggest that the kinematic properties originating from the balance maintenance constraint allow the actual weight to be detected despite attempted deception. However, they also note that slower lifts performed in an attempt to imitate lifts of heavy weight are effective in conveying heaviness.

Because the deceptive intention *is* conveyed successfully, deceptive movements must, at least, approximate some kinematic property of lifts that varies with the amount of weight lifted. The question is, what is that property? Runeson and Frykholm refer, in this regard, to the speed of the lift suggesting that heavier weights are lifted more slowly. However, the "speed" of lift is ambiguous. This could mean either the average velocity of the box over the lift or the peak velocity reached by the box during the lift. The two could vary independently in lifts.

An alternative to "speed" is a specific pattern of variation in velocity over the course of a lifting motion. Runeson (1974) discovered that observers are able to identify specific forms of motion of an object along a path. For instance, an impact-like event can be distinguished from constant force motion (Bingham & Runeson, 1983). The kinematic property allowing identification is the form of the motion as expressed on the phase plane,[1] that is, the specific *pattern of variation in velocity of a moving object over displacement.*

The kinematic form of a lifting movement is different from the speed of a lift because the speed can be scaled without change of kinematic form. (See, e.g., Hollerbach & Flash, 1982.)[2] Varying the average velocity or the total duration of a movement within scaling limits does not affect its observed identity as long as the pattern of relative variations in velocity over position is preserved (Runeson, 1974). Human limb movements exhibit characteristic patterns of variation in velocity (Atkeson & Hollerbach, 1984; Greene, 1982). It may be that lifters voluntarily performing slow lifts to convey heaviness of weight are attempting to imitate some aspect of a change that occurs in the kinematic form of a lift with heavier weights without faithfully reproducing the entire change.

Might the dynamics of force generation in human movement contribute directly to the informative value of kinematic pattern in the visual perception of lifted weight? Another reason to study the trajectory of the lifted object as a source of information for lifted weight is that it focuses on the properties of muscle and its connections to limb segments as a constraint on the form of human movement. The actuators in human movement exhibit a collection of distinctive properties relative to their capacities for force generation, for example, the force-length and force-velocity relations for muscle fiber bundles, recruitment patterns for muscles, elastic storage capacities of tendons, ligaments, and muscles, and frequencies and amplitudes of contraction that exhibit optimum power output or optimum energy consumption (Alexander, 1984; Astrand & Rodahl, 1977; Cavagna, Heglund, & Taylor, 1977; Fedak, Heglund, & Taylor, 1982; Giovanni, Cavagna, Citterio, & Jacini, 1980; Harrison, 1963; Heglund, Fedak, Taylor, & Cavagna, 1982; Hill, 1970; Hof, Geelen, & Van Den Berg, 1983; McMahon, 1984; Taylor, 1978, 1980; Taylor, Heglund, McMahon, & Looney, 1980). These properties constrain the commonly observed forms of movement in mammals. In particular, Harrison (1963) has found that specific trajectories correspond to specific levels of maximum power output in human limb motion. The complex, nonlinear properties of the torque generators as mobilized by the action system operating in a preferred mode may interact with specific levels of requisite torque in a movement so as to produce trajectories that are specific to the torque level.

To test the possibility that observers can distinguish among lifted weights on the basis of patterns of variation in velocity over the course of a lift, I studied one arm curls as a means of isolating variations in velocity during a lift. Balance-preserving leans were eliminated during curls by externally supporting the body and "freezing out" sway.

A second issue raised by Runeson and Frykholm's results is that of scaling information. On what basis are observers able to scale a kinematic property so as to be able to judge accurately the underlying kinetic value, for example, metric amount of weight? Without a basis for scaling, observers would be able to judge only ordinal relations in relative variations of lifted weight. They could say that one weight was heavier than another, but they could not assign particular weight values. However, Runeson's observers accurately judged the metric values of weight. Runeson and Frykholm *apparently* provided the basis for scaling by including a standard in their experimental design. Observers were shown a sample midrange lift and told the correct value of the weight prior to each block of five judgment trials. Traditionally, the value attached to a standard in magnitude estimation is arbitrary (Gescheider, 1976; Stevens, 1975). However, the standard in Runeson and Frykholm (1981) was assigned a nonarbitrary value on the metric scale of weight that apparently indexed the appropriate scale for subsequent judgments. On the assumption that the standard provides the entire

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[1] The "phase plane" is a graph of velocity versus position. See, for example, McGinnis and Newell (1982) and Nelson (1983).

[2] Hollerbach and Flash (1982) demonstrate velocity scaling without change of form in a velocity–time plot; however, the present study involves the form of a velocity–position plot. What are the essential properties that might distinguish among phase plane forms? Candidates include symmetry properties, the number of critical points in the curve, and the specific behavior of various derivatives along the curve providing a local description of its shape (O'Neill, 1966). Phase plane curves for human limb movements typically are unimodal with a single point of inflection, bilateral symmetry, and restricted variations along the curve in both curvature and rate of change of curvature. Peak velocity of movement is represented by the height of the velocity–position curve at the inflection point. This height can be scaled to a degree determined by the amplitude without appreciable change in the curvature or rate of change of curvature along the curve. By contrast, a change in kinematic form could mean allowing the rate of change in curvature to increase sharply at points bounding a portion of the curve along which curvature approaches zero. The resulting curve would look more like a square than a semicircle.

basis for scaling, the displays would specify only ordinal relations among lifted weight values.

However, the assumption that a standard could provide the *entire* basis for scaling cannot be correct. Weight is measured on a ratio scale. In scaling ordinal relations among weights so that ratio scale values can be specified, both the size of intervals between successive weights and the size of the distance between any one particular weight in the range and zero must be determined. A standard could provide a basis for the latter. However, the standard could not provide a basis for scaling the size of intervening intervals. Therefore, given Runeson and Frykholm's results, the displays must, at least, provide a basis for scaling the successive intervals between ordered weight levels. Given this necessity, the following question arises: Do the displays contain a basis allowing the intervals between weights lifted to be scaled without simultaneously scaling the weights relative to zero?

In this instance, four levels of scaling can be distinguished as opposed to the traditional three levels, as follows: *ordinal relations,* for example, A is heavier than B, which is heavier than C; *intervals scaled for relative size,* for example, the difference between B and C is twice the difference between A and B; *intervals scaled for absolute size,* for example, B is 5 lb heavier than A, but C is 10 lb heavier than B; and *ratio* scale, for example, A is 5 lb, B is 10 lb, and C is 20 lb. Traditionally, the latter two levels are collapsed. In the present study, they must be distinguished because the standard does not establish the size of intervals between weight levels. It relates only a single weight level to zero. Thus, the absolute size of intervals and the absolute distance from zero of the overall relative range[3] of weights can vary independently, although there is likely to be some interaction. The relative sizes of intervals must be determined by the kinematics of these displays. The displays must contribute as well to the determination of the absolute size of intervals, although the standard might act to constrain their size further. What remains is for the relative range of weights to be scaled to zero. Overall, the standard may provide merely an improved basis for scaling over that available in the displays.

More generally, the second question addressed in this research is as follows: To what extent is the basis for scaling that must exist in the observed displays improved by the experimenter through provision of a standard? This question was investigated as follows: Observers were asked to judge lifted weight in patch–light displays without the benefit of a standard trial. Subsequently, the judgment task was repeated with the inclusion of a standard in the design. The effect of scaling between the display-only and display-with-standard conditions was tested by examining variations in the accuracy of judgments.

Within the context of the question of accuracy and bases for scaling, a third issue was investigated, namely the sensitivity of alternative metrics to changes in the bases of scaling that might be used by observers in judging lifted weight.[4] The alternative scaling bases include both those intrinsic to the observed displays, and thus intrinsic to the lifting activity, and those provided extrinsically by the experimenter. Metrics intrinsic to the lifting may be less sensitive to the presence or absence of extrinsic scaling bases than is an extrinsic metric like the pound or kilogram. Three metrics varying in the standard used to establish size of units were used. The first was the British scale of weight in which the unit is the pound.[5] The standard for the second was the maximum weight that an observed lifter was able to lift in a one-arm curl. Observers judged the percentage of effort for the lifter where 100% corresponded to the maximum lift. The standard for the third metric was the maximum weight that an observer was able to lift in a one-arm curl. Observers judged percentage of effort for themselves if they were to lift in the same manner the observed weight. (Before judgment trials, observers were allowed to assess their own lifting abilities.) Subsequently, judged weight values in pounds were divided by the *actual* maximum weight for the observed lifter. These derived percentage judgments could be compared then with the two judgments of percentage of effort to reveal relative variations as a result of changes in scaling bases.

Experiment 1

Experiment 1 investigates three different factors. First, the informative value of the kinematic form of a lift was tested in a single degree-of-freedom lift. Lifters lifted varying amounts of weight in one-arm curls performed by using only the elbow to move the weight. Second, the possibility that a basis for scaling this kinematic form is available in the patch–light displays was tested by requiring observers to judge lifted weight without and with the benefit of a standard. In addition, observers judged lifted weight with the benefit of the lifter's maximum lift value as well as a standard. Finally, the sensitivity of different metrics to alternate scaling bases was explored by asking observers to judge lifted weight along three different measures: weight in pounds, percentage of effort for the lifter, and percentage of effort for the observer.

Method

Observers judged lifts performed by 3 different lifters. Each lifter lifted five levels of weight. Each lifter performed two lifts with each weight for a total of 10 lifts. Each lift consisted of three one-arm curls executed consecutively. Observers made three different judgments for each lift each time it was seen in three different scaling conditions. Repetitions of weight levels were blocked within lifter. In turn, lifter was blocked inside scaling condition. The three types of judgment crossed all blocked factors.

Apparatus. A one-handed barbell set was used that allowed the amount of weight to be varied in 5-lb increments from 5 lb (2.27 kg) to 45 lb (20.41 kg). For recording, a Sony ½-in. AV-tape system was used

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[3] The relative range of weight values is equal to the sum of the intervals between successive weights scaled for absolute magnitude.

[4] Scale, meaning size or magnitude, is a property that is associated with other properties of an event. *Scaling basis* refers to sources of information about scale in an event. Metrics involve the act of measurement where scale is to be represented and communicated. A metric establishes units for measurement as well as procedural criteria for applying units. The results of measurement are subject to variation, depending on the relation between a metric and sources of information about scale. Consider the light year versus the meter versus stride length versus highway driving time as metrics for the measure of distance. Appropriate domains of application for each of these metrics are determined by their relation to scaling bases.

[5] British system units are used in the judgment study because participants were most familiar with these units.

with a Sony camera and a 19-in. black-and-white screen monitor. The lifters were dressed in dark pants and a dark navy blue hooded pullover shirt. Strips of light tan masking tape were attached to this shirt at the head, the hip, the shoulder, just above and below the elbow, and just above the wrist. Masking tape also was attached in a cross to a round, black, felt-covered disk, which was attached to the end of the barbell lifted. Styrofoam was used to fashion a head rest and an elbow rest for the lifters.

Lifters. Three lifters were employed—one female, 163 cm tall and 56.7 kg in weight; and two males, one 170 cm tall and 72.6 kg in weight and the other 175 cm tall and 77 kg in weight. All were at least moderately experienced in fitness activities. The second male lifter lifted weights regularly and had somewhat greater than normal muscle mass in his arms.

Recording procedure. During the lifts, lifters were required to lean their backs flat against a wall with their feet placed so that the heels were approximately 10 in. from the wall. With the lifter's body weight leaned firmly against the wall, the occurrence of any posture preserving sway or leaning during the lifts was prevented. Lifters wore the tape-bearing shirt with the hood pulled up to completely cover the head as seen from the side. Lifters positioned their head on a fitted styrofoam head rest that held their head in an upright position. They were instructed not to move their heads during the lifts. Lifters rested their right elbows on a styrofoam block, which was adjusted to position the upper arm parallel to gravity. Lifters did not remove their elbow from this support during the lifts.

The type of lift performed is commonly referred to as a one-arm curl. Each lift consisted of three flexion extensions of the right arm in sequence without pause so that the forearm traveled 35°–45° to either side of a 90° angle with the upper arm. The barbell was gripped firmly in the hand. Each recorded lift began with the lifter's holding the barbell with the elbow extended to about 135°. Just before each lift, the experimenter placed the barbell in the lifter's hand. Recording then began within 5 s. The lifter performed the three curls, finishing in the same position as at the beginning. After the lift, recording was stopped, and the experimenter immediately relieved the lifter of the weight. Lifts were timed at least 2 min apart in recording sessions to avoid any pronounced fatigue effects (Astrand & Rodahl, 1977). Lifters were instructed to perform lifts at their preferred rate. They were asked to perform the lifts in the most comfortable way, given the constraints of the task, as if they were to lift all day long.

Each lifter lifted five different levels of weight. For each lifter, the maximum amount of weight that she or he could lift, accurate to the nearest 5-lb increment, was established on a day preceding the recording session. It was not required that the lifter always be able to lift the maximum weight successfully three times. During one or two of the recorded lifts with maximum weights, only one or two full amplitude curls were performed successfully, followed by an attempt in which the forearm approached the right-angled position between forearm and upper arm during flexion, and then the forearm extended.

The female lifter lifted 20 lb (9.07 kg) as her maximum. The remaining weight levels were 15 lb (6.80 kg), 10 lb (4.53 kg), 5 lb (2.27 kg), and 0 lb. The 0-lb lifts were performed with the felt-covered cardboard disk attached to a cardboard tube. The first male lifted 35 lb (15.87 kg) as his maximum. The remaining weight levels were 30 lb (13.60 kg), 25 lb (11.34 kg), 20 lb (9.07 kg), and 15 lb (6.80 kg). The second male lifter lifted 45 lb (20.41 kg) as his maximum. The remaining weight levels were 35 lb (15.87 kg), 25 lb (11.34 kg), 15 lb (6.80 kg), and 5 lb (2.27 kg). Henceforth, these lifters will be referred to as the Max20, Max35, and Max45 lifters, respectively.

The lifts were recorded from the right side of the lifter, with the camera positioned approximately 4 m from the lifter and at shoulder height. The zoom was adjusted so that each lifter just filled the vertical extent of the screen from the top of his or her head to mid-thigh. For each lifter, lifts with each of the five levels of weight were recorded two times in two random order blocks. Thus, each lifter was recorded performing 10 lifts, each lift consisting of three curls. In addition, a 15-lb (6.80-kg) lift was recorded preceding each block of five lifts to serve as a standard.

After the data had been collected, an error was discovered in the recording of displays of Max45 lifter. A 35-lb (15.87-kg) weight (fourth weight level) had been substituted for the 25-lb (11.34-kg) weight (third weight level) in the second block of lifts. Thus, observers saw only one 25-lb (11.34-kg) lift and three 35-lb (15.87-kg) lifts. For subsequent analysis of the data for this lifter, judgments at each weight level were averaged for each observer, resulting in a single judgment score for each weight level per scaling condition and per judgment type.

Observers. Nine male University of Connecticut undergraduates participated as observers. All were paid $3.50 for their time. All had been familiar with the British system of measure since childhood. Only males were allowed to participate because pilot studies indicated that males and females might differ in performance.

Experimental procedure. The maximum weight that each observer could lift in a one-arm curl was determined. These lifts were similar to those recorded except participants rested their elbow on their hip and lifted a box by an attached handle. The box was used so that weight level could be manipulated easily and quickly by adding or removing measured bags of sand. The resulting weight value was accurate to the nearest 5-lb increment. Observers were instructed to write this value at the top of each subsequent protocol sheet.

The observers were seated four or five at a time, 2–3 m from the viewing screen in a normally lit room. A 19-in. black-and-white screen monitor was used with contrast and brightness turned down so that events were shown as bright patches on a dark background. For each lift, observers were required to make three judgments. First, they judged the percentage of effort expended by the lifter (PEL) in lifting each weight. One hundred percent effort was defined as occurring when the lifter was lifting the most she or he could possibly lift in a one-arm curl. Second, observers judged the percent of effort they themselves, the observers, (PEO) would have to expend to lift in the same manner the same amount of weight seen lifted. Third, they judged the amount of weight lifted in pounds (WT). Observers had a very brief period between recorded lifts (approximately 4 s) in which to make and write all three judgments. Thus, first-impression, intuitive, off-the-cuff judgments were encouraged. The experimenter announced the beginning of each lift by calling out the number of the trial for that lifter and condition. In this way, observers knew when to look up for the next trial.

Trials were blocked by lifter within scaling condition. The order of scaling conditions was always the same. First, in the display-only condition, no standard was provided. No mention was made of scaling in this condition, and observers judged the standard lifts along with all others. All 10 lifts plus 2 standard lifts for all 3 lifters were observed and judged in the order Max20, Max35, and Max45. Second, in the display-with-standard condition, the 15-lb (6.80-kg) standards preceding each block of five lifts were labeled as such on the protocol sheets and verbally by the experimenter to be sure that observers noticed them each time. Finally, in the display-with-standard-and-maxlift condition, the 15-lb (6.80-kg) standards were provided again plus the maximum amount of weight that could be lifted by each lifter. These latter values were written on the protocol sheets below the column where judgments for the lifter were to be written. In addition, the experimenter verbally reminded observers of the corresponding "maxlift" value preceding the set of lifts by each lifter. Protocol sheets were collected from observers after each scaling condition, and new sheets were distributed.

During the initial instructions a few randomly selected lifts were shown as examples. Participants were told not to communicate with each other during the session nor to disclose any other reactions during the task. Observers were given no other information about the lifters.

In particular, no information was provided concerning the sex, size, or physical condition of the lifters.

Design. The main factors were weight level (1–5), scaling (display only, display with standard, display with standard and maxlift), and judgments (weight [WT], percentage of effort for the lifter [PEL], percentage of effort for the observer [PEO]). Lifters (Max20, Max35) and repetition of weight levels (two blocks of five levels) were included also as factors forming a five-way $5 \times 3 \times 3 \times 2 \times 2$ factorial design with nine observations in each cell. The design for the Max45 lifter excluded repetition of weight levels resulting in a four-way $5 \times 3 \times 3 \times 3$ factorial design with nine observations in each cell. All factors were within subjects.

Results and Discussion

For graphing and comparison, PEO and WT judgments were scaled to the observed lifter's capabilities. WT judgments were expressed as a percentage of the maximum amount of weight that could be lifted by a lifter. Judged weight values for each lifter were divided by the maximum weight *actually* lifted by that lifter and multiplied by 100, that is, WT% = WT% ÷ maxlift × 100. These transformed weight judgments (WT) are referred to as WT% (weight percent). PEO judgments were scaled as follows: The ratio of the maximum weight that could be lifted by each observer and by each lifter observed was used as a multiplying factor adjusting PEO values, that is, adjusted PEO = PEO × (maxlift for observer ÷ maxlift for lifter). If PEO is approximated by (lifted weight ÷ maxlift for observer), then this adjustment is (lifted weight ÷ maxlift for observer) × (maxlift for observer ÷ maxlift for lifter) = (lifted weight ÷ maxlift for lifter), which is comparable to PEL. Adjusted PEO values are referred to simply as PEO. All three judgments (WT, PEL, PEO) thus are expressed as percentages (WT%, PEL, PEO) scaled to the observed lifter's capabilities.

The results are summarized in Figures 1 and 2. Results show an overall increasing trend in judgments over increasing weight levels. In addition, PEL judgments remained invariant across the three scaling conditions, whereas PEO and WT judgments changed. PEO judgments changed less than WT judgments because PEO judgments were more accurately scaled in the first scaling condition. Accuracy improved over scaling conditions.

The first question investigated in this experiment was whether the kinematic form of a lift enables observers to distinguish relative amounts of lifted weight. The results indicate that they can. In Figure 1, all judgment curves for all 3 lifters exhibit an increasing trend with increasing weight levels. A repeated measures analysis of variance (ANOVA) was performed on the data for the Max20 and Max35 lifters, with weight level, repetition of weight levels, lifter, scaling, and judgment as factors.[6] Weight level was significant, $F(4, 32) = 136.55$, $MS_e = 1467$, $p < .001$, and accounted for the lion's share of the variance, 31% of the total sums of squares.

Lifter was significant, $F(1, 8) = 20.28$, $MS_e = 4060$, $p < .002$. Lifter was significant also in all its interactions with weight level, scaling, and judgment. Because results for lifters are different and because the data for the Max45 lifter could not be included in an overall analysis, a separate repeated measures analysis of variance was performed on the data for each lifter with weight level, repetition of weight levels (except for Max45 data), scaling, and judgment as factors. Weight level was significant ($p < .001$) and accounted for the majority of the variance in all cases. For the Max20, Max35, and Max45 lifters, weight level accounted for 32%, 40%, and 60% of the total sums of squares, respectively. Thus, the weight level factor is significant and consistently accounts for large proportions of the variance both overall and for each lifter.

The second issue investigated in this experiment was scaling. In this regard, emphasis must be placed on the fact that the displays contribute more to the observers' judgments than the mere ability to distinguish among increasing levels of lifted weight. The relative size of the intervals between weight levels was determined by scaling bases intrinsic to the displays. In Figure 1, the form of all three judgment curves for each lifter in the display-only condition is comparable, as is the form for curves across all three scaling conditions. There is some change in the slope of curves corresponding to changes in judged amounts of weight over scaling conditions—both decrease. However, because adjustments in curve positions and slopes are limited, the displays must provide the basis for scaling the absolute size of intervals between weights and the distances of the range from zero within a restricted degree of accuracy.

There is a slope change over scaling conditions in WT and PEO judgments for the Max20 lifter. The slopes for weight judgments, plotted versus physical weight in Figure 2, were computed in linear regressions (see Table 1). The slope in the third scaling condition dropped to 0.53 from 1.05 in the first scaling condition. This change in slope accompanies a drop in vertical position of the judgment curve. Slopes also decrease for the Max35 and Max45 lifters, but to a much smaller degree corresponding to a smaller change in the vertical position of the entire curve. In the separate ANOVAs for the data of each lifter, the Weight Level × Scaling interaction was significant only for the Max20 lifter, $F(8, 56) = 3.74$, $MS_e = 1465$, $p < .002$. This result indicates that there is some interaction between scaling the size of the range of weights lifted (i.e., the slope) and scaling the distance of the entire range from zero (e.g., the distance of the midrange from zero). The interaction was not significant for the Max35 and Max45 lifters; however, their curves did not vary greatly in distance from zero.

Changes in the size of the range with changes in distance from zero essentially stretch and compress judgment curves of otherwise relatively invariant form established in the display-only scaling condition. The variation in the distance of the range of judged weights from zero is restricted. Heaviest mean judged weights do not exceed a value of about 50 lb (22.68 kg). This indicates that the displays alone allow scaling of both the range of weights lifted and the distance of that range from zero within a restricted degree of accuracy. Additional bases for scaling may then enhance the accuracy.

In summary, the essential shape and approximate location and slope of the judgment curves are determined by observation of the patch-light displays alone. For each lifter, changes in curves for the different judgments across scaling conditions are primarily adjustments of relative position among curves, with some corresponding change in slope. These changes reflect fine

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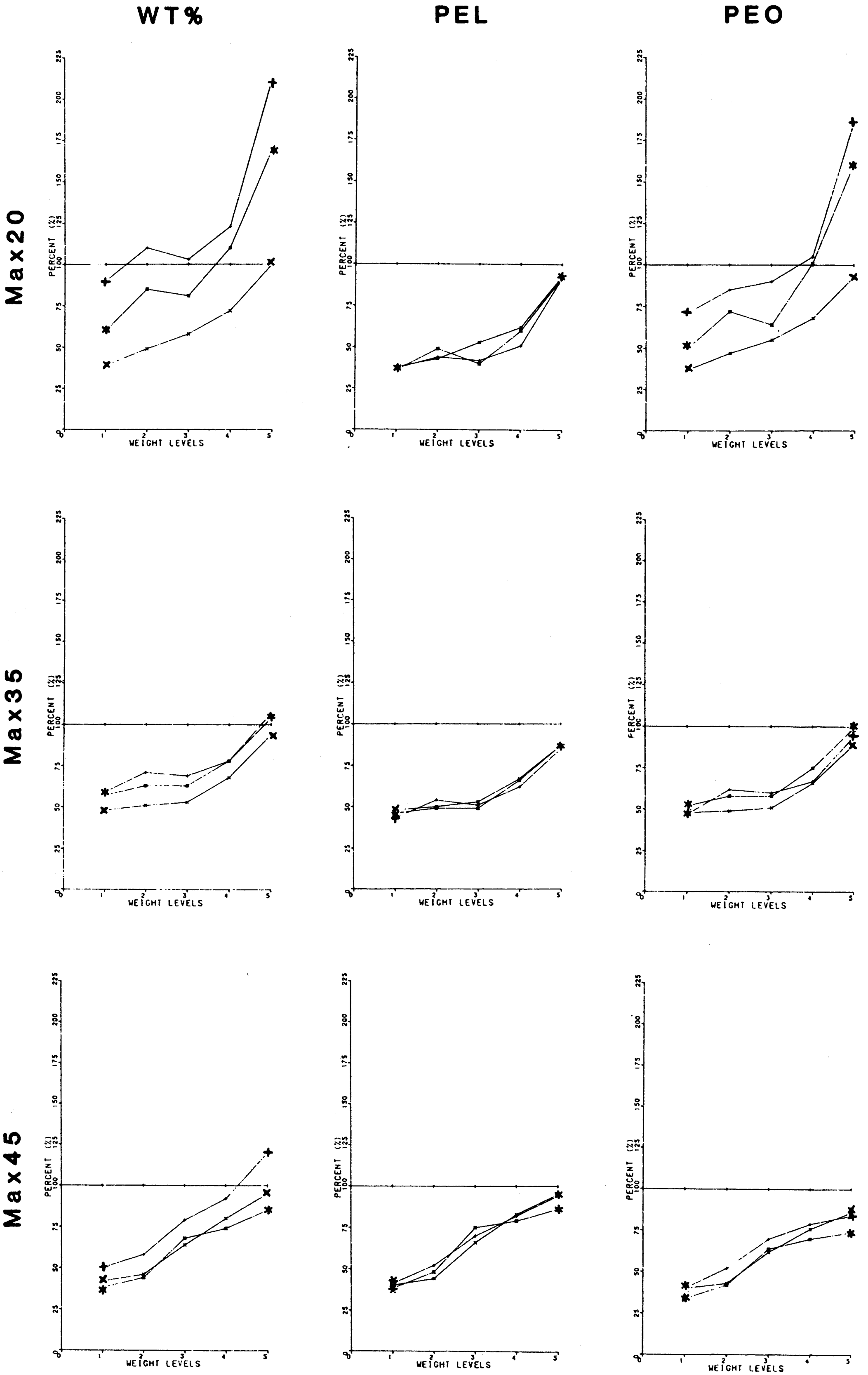
[6] The data for the Max45 lifter did not include the repetition-of-weight-levels factor for purposes of analysis and so could not be included in this ANOVA.


WT%
PEL
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Max20
Max35
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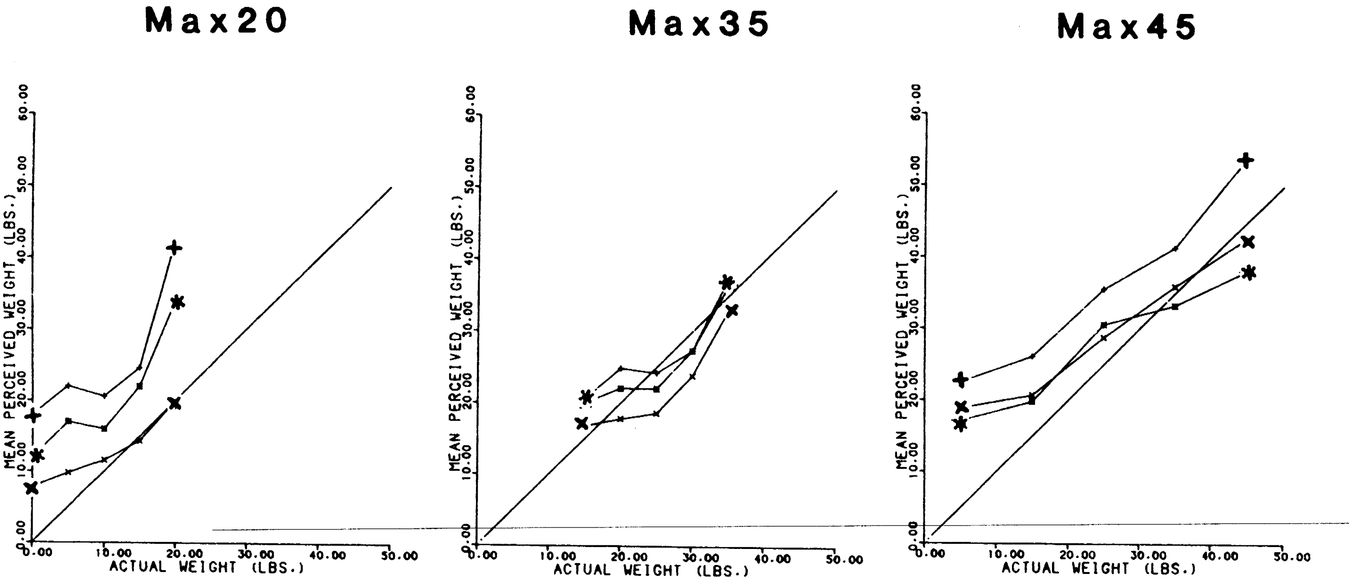

Figure 2. Mean weight judgments versus actual weight over three scaling conditions for the Max20, Max35, and Max45 lifters. (Display only = +; display with standard = *; display with standard and maxlift = x.)

tuning of judgments allowed by bases for scaling in addition to the bases in the displays.

In the separate ANOVAs for the data of each lifter, the scaling factor was significant only for the Max20 lifter, $F(2, 14) = 11.34$, $MS_e = 7368$, $p < .002$. Scaling was marginal for the Max45 lifter, $F(2, 14) = 3.65$, $MS_e = 778$, $p < .054$. Judgment was significant for all 3 lifters, accounting for the largest percentage of the total sums of squares for the Max20 lifter (13.05%, $p < .001$) and for the smallest portion for the Max45 lifter (1.81%, $p < .02$). However, the Scaling × Judgment interaction was significant for all 3 lifters. The effect was strongest for the Max20 lifter ($p < .001$) and weakest for the Max45 lifter ($p < .05$).

Curves for the three judgments squeeze together over the three scaling conditions. To ascertain whether each type of judgment was affected by scaling condition, a repeated measures analysis of variance was performed on the data for each lifter and each judgment type with weight level, repetition of weight levels (except for Max45 data), and scaling as factors. The results for scaling show that WT and PEO judgments change over scaling conditions, whereas PEL judgments remain invariant. Scaling was significant for WT% for the Max20 and Max45 lifters—more so for Max20 ($p < .001$), accounting for 22% of the total sums of squares, less so for Max45 ($p < .01$), accounting for 7.6% of the total sums of squares. Scaling was marginal for WT% for the Max35 lifter ($p < .072$). Scaling was significant for PEO only for the max20 lifter ($p < .001$), accounting for 14% of the total sums of squares. Scaling was not significant for PEL judgments for any lifter.

These results indicate that the bases for scaling provided by the experimenter in the second (display with standard) and third (display with standard and maxlift) scaling conditions affected the relative positions of curves representing judgments of weight and of percentage of effort for the observer. The effect was much weaker for judgments of percentage of effort for the observer than for judgments of weight. Judgments of percentage of effort for the lifter remained unaffected.

That the same trends were obtained for all 3 lifters observed can be seen in Figure 1, where the results are graphed by judgment type. The PEL curves remain invariant over scaling conditions. WT% and PEO curves both change, generally moving down over scaling conditions. WT% and PEO curves change to a much smaller degree for the 2 male lifters, Max35 and Max45, than for the female lifter, Max20. PEO curves are much closer to PEL curves than are WT% curves in the display-only scaling condition. The effect of scaling conditions on PEO judgments was weaker because those judgments were scaled more accurately in the first scaling condition.

The accuracy of weight judgments is shown in Figure 2, where mean judged weight values for the three scaling conditions are plotted against actual weight levels. Initially, judged

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Figure 1. Mean WT% (percentage of weight lifted in pounds), PEL (percentage of effort for lifter), and PEO (percentage of effort for observer) judgments over three scaling conditions plotted by judgment type for the Max20, Max35, and Max45 lifters. (The ordinate is percent and represents the range from 0 to 225 by increments of 25; the abscissa is weight levels and represents the range from 1 to 5. A line for 100% is marked across weight levels for reference. Display only = +; display with standard = *; display with standard and maxlift = x.)

Table 1
Linear Regressions on Weight Judgments Versus Actual Weight

	Lifter		
Scaling condition	Max20	Max35	Max45
Display only	$Y = 1.05X + 15.08$ $r = .59$ $r^2 = .35$ $p < .01$	$Y = 0.73X + 8.75$ $r = .58$ $r^2 = .34$ $p < .01$	$Y = 0.74X + 16.57$ $r = .77$ $r^2 = .59$ $p < .01$
Display with standard	$Y = 1.00X + 1.06$ $r = .66$ $r^2 = .44$ $p < .01$	$Y = 0.89X + 3.94$ $r = .59$ $r^2 = .35$ $p < .01$	$Y = 0.53X + 14.05$ $r = .78$ $r^2 = .61$ $p < .01$
Display with standard and maxlift	$Y = 0.53X + 7.53$ $r = .72$ $r^2 = .52$ $p < .01$	$Y = 0.66X + 6.16$ $r = .65$ $r^2 = .43$ $p < .01$	$Y = 0.54X + 15.20$ $r = .79$ $r^2 = .62$ $p < .01$

weight tends to be overestimated, but judgments improve in accuracy over scaling conditions, as shown by increasing values of r^2 in Table 1. Weight judgments in the third scaling condition are reasonably accurate, with a marked tendency to overestimate lighter weights. Computed regression lines had slopes of .53, .66, and .54 for Max20, Max35, and Max45, respectively. Intercepts were 7.53, 6.16, and 15.20, respectively. The somewhat shallow slopes and high intercepts reflect the tendency to judge light weights as heavier than they are, that is, light and medium weights are more difficult to discriminate. Variations in actual weight level accounted for 52%, 43%, and 62% of the variance in judged weight for the Max20, Max35, and Max45 lifters, respectively. This reflects a reasonable degree of accuracy, considering the apparent poorness of the viewing conditions in this experiment (i.e., the strongly restricted motions of a few patches). These conditions apparently did not reflect a strict paucity of information.

Judgment curves are not linear with weight. The curves are flatter at lower and middle weight values, growing steeper only for larger relative amounts of weight. Runeson and Frykholm's (1981) judgment curves also exhibited a tendency towards a shallower slope at lower weight levels. This trend is much more pronounced in the present data.

Close examination of the displays and of the recording procedure reveals three factors that should be controlled to ensure that only the kinematic form resulting from movement at a single joint—that is, only patterns of variation in velocity over position—is being tested as a kinematic property indicative of lifted weight. First, a reflective patch was attached to the shoulder of lifters in the present study. Some shoulder movement can be detected during lifts, particularly during lifts of heavier weights. Second, lifters lifted weights very close to their absolute maximum. The result was that not all lifts included three full amplitude curls. To eliminate large variations in amplitude, lifts should be recorded only with weight that lifters can consistently lift in three full amplitude curls. Finally, the wrist joint of the arm used to perform lifts was not constrained. A brace of the sort used to immobilize wrist fractures could be employed to ensure that movement occurs only at the elbow of the lifter.

Experiment 2

Experiment 2 was performed as a replication of Experiment 1, with modifications in the patch–light recording procedure ensuring isolation of variation in velocity of movement at the elbow as the only kinematic property in the display that might vary with lifted weight. The resulting judgment curves were examined for replication of the trend away from linearity exhibited in Experiment 1. In addition, only two scaling conditions were used, namely the display-only and the display-with-standard conditions. Finally, the design of both Experiments 1 and 2 included repeated observation and judgment of patch–light displays over the addition of bases for scaling. A control on this repetition design tests whether results attributed to the addition of scaling bases might be attributed to repeated observation of displays with perhaps improved detection of an inherent basis for scaling. In a control task, observers performed the judgment task twice with the same displays but without the addition of a standard in the second repetition.

Method

Apparatus. The recording and weight lifting equipment used were the same as in Experiment 1 except that a Panasonic camera was used. The different response characteristics of this camera required changes in the lighting and reflective patches. The lifters were dressed in dark pants and a dark black turtleneck shirt. Strips of retroreflective tape attached to strips of white linen were pinned around the lifter's head and elbow. A cardboard disk attached to the end of the barbell was covered with white reflective paper. Styrofoam was used to fashion a head rest and elbow rest as in Experiment 1. Unlike in Experiment 1, these rests were visible as bright patches in the display of Experiment 2. A 115-V movie light with parabolic reflector was placed adjacent to the camera directed at the lifter. Lifters each were fitted by a pharmacist with a wrist brace of the type used to immobilize wrist fractures. The brace prevents rotation at the wrist joint. The brace did not interfere with the lifter's ability to grasp the barbell.

Lifters. Three lifters were employed. All were male. The 3 weighed 86 kg, 80 kg, and 77 kg and were 188 cm, 180 cm, and 175 cm tall, respectively. All were at least moderately experienced in fitness activities including weight lifting. The first and third lifters lifted regularly, and the third lifter had somewhat greater than normal muscle mass in his arms.

Recording procedure. The procedure was the same as in Experiment 1 except for the following aspects. Immediately preceding the recording session, the maximum amount of weight that could be lifted consistently in a one-arm curl was determined for the lifter. It was required that the lifter consistently be able to lift the weight in three consecutive full amplitude curls. Maximum consistent lift was determined within 5 lb. If required to lift the weight successfully only once or twice, lifters might have handled the next 5-lb increment. The first lifter lifted 35 lb (15.87 kg) as his maximum; the second lifter lifted 30 lb (13.60 kg) as his maximum; the third lifter lifted 35 lb (15.87 kg) as his maximum. Weight levels increased by 5-lb equal increments for all lifters. Henceforth, these lifters will be referred to as practice, Max30, and Max35, respectively, because recordings from the first lifter were used as practice trials.

For each lifter, lifts with each of the five levels of weight were recorded three times in random order blocks. Each lifter was recorded performing 15 lifts, each lift consisting of three curls. In addition, a midrange weight lift was recorded for each lifter preceding each block of five lifts to serve as a standard. The standard for the practice lifter was 25 lb (11.34 kg); for the Max30 lifter, 20 lb (9.07 kg); and for the Max35 lifter, 25 lb (11.34 kg). The first block of lifts for each lifter was treated as practice trials in both scaling conditions. When these recordings were displayed in subsequent experimental sessions, the video monitor was adjusted so that the head patch for the Max35 lifter could not be seen. This was possible because this patch was somewhat dimmer than other patches in recordings and thus could be eliminated.

Observers. Fifteen male University of Connecticut undergraduates from an introductory course in psychology participated in the experiment for course credit. For the control task, an additional 10 male undergraduates participated for course credit. All had been familiar with the British system of measure since childhood.

Experimental procedure. These procedures were the same as in Experiment 1 except that only two scaling conditions were included, display only and display with standard. Observers were required to make the same three judgments as in Experiment 1, namely, weight (WT), percentage of effort for the lifter (PEL), and percentage of effort for the observer (PEO). However, 100% effort was defined as occurring when the lifter was lifting the most he could lift consistently in three consecutive full amplitude one-arm curls. The displays were always shown in the order of practice lifter, Max30 lifter, and Max35 lifter in the two scaling conditions, display only and display with standard.

For the control task, the procedure was the same as above with two exceptions. The first is that no standard was provided in either scaling condition. Thus, scaling conditions become simply repetitions. The second difference is that observers were required to make only two judgments for each lift: percentage of effort for the lifter (PEL) and percentage of effort for the observer (PEO). Observers were not instructed to judge the amount of weight lifted. With no scaling standard provided, this task could have become very frustrating. This is particularly true if one were attempting to judge weight values. Because the questions posed in this experiment could be assessed by way of the PEL and PEO judgments alone, the weight judgments were excluded so as to avoid frustrating participants so much as to affect their diligence in performing the task.

Design. The main factors were weight level (1–5), scaling (display only, display with standard), and judgment (WT, PEL, PEO). Lifters (Max30 and Max35) and repetition of weight levels (two blocks of the five weight levels) were included also as factors forming a five-way 5 × 2 × 3 × 2 × 2 factorial design with 12 observations in each cell. All factors were within-subjects.

For the control task, the design was the same except that the second scaling factor was also display only, and judgments were PEL and PEO for a five-way 5 × 2 × 2 × 2 × 2 design with 10 observations in each cell.

Results and Discussion

The results are summarized in Figures 3 and 4. Results show fairly flat or descending or gently increasing curves for light-to-medium weight levels and increasing curves for medium-to-heavy weight levels. Results show also that PEL judgments remain invariant over scaling conditions, whereas PEO and WT judgments change over scaling conditions. PEO judgments change less than WT judgments because PEO judgments were scaled more accurately in the initial scaling condition. Accuracy improved over scaling conditions. However, accuracy was not as good as in Experiment 1.

For graphing and comparison, PEO and WT judgments were transformed as described in Experiment 1. The result is that all three judgments are expressed as percentages (WT%, PEL, and PEO), scaled to the observed lifter's capabilities. In Figure 3, the three judgments were plotted as in Figure 1 of Experiment 1.

The first question addressed in Experiment 2 was whether the kinematic form of a one-arm, one-joint curl enables observers to distinguish relative amounts of lifted weight. Experiment 2 was performed as a replication of Experiment 1, with the pattern of variation of velocity at the elbow isolated as the only kinematic property available to observers of these point-light displays. The results indicate that observers are able to discriminate lifted weight to a very limited degree.

A repeated measures analysis of variance was performed on the data with weight level, repetition of weight levels, lifter, scaling, and judgment as factors. Weight level was significant, $F(4, 44) = 40.45$, $MS_e = 526$, $p < .001$, and accounted for the largest portion of the variance after units, 9.41% of the total sums of squares. Lifter as a factor was not significant and accounted for almost none (0.08%) of the variance; however, there was a significant Lifter × Weight Level interaction ($p < .001$), accounting for 1.22% of the total sums of squares.

In Figure 3, judgment curves are flat or actually exhibit a decreasing trend over increasing amounts of weight at low-to-medium weight levels while increasing or steeply increasing trends are exhibited at medium-to-high levels of weight. Observers had difficulty in distinguishing weights that were of light or medium weight relative to the lifter's ability. However, as weight became heavy for a particular lifter, observers were able to perceive the increasing difficulty experienced by the lifter in performing the lift. The judgments reflect a nonlinear relation between increases in weight and the lifting capabilities of the lifter. An anomalous increase in judgments with lighter weights occurs for the Max30 lifter, whose head patch was visible in the displays. For some reason, the lifter made very slight nodding movements once when lifting the lightest weight level, and this apparently affected judgments. In debriefing, observers reported difficulty in discriminating light from medium weight levels. This difficulty very likely made observers sensitive to subtle changes. A nodding of the head in tonic neck response might be expected to accompany the lifting of a heavy weight. Trend analyses were performed to test whether a nonmonotonic or a flat-then-rising trend accounts for a greater portion of the vari-

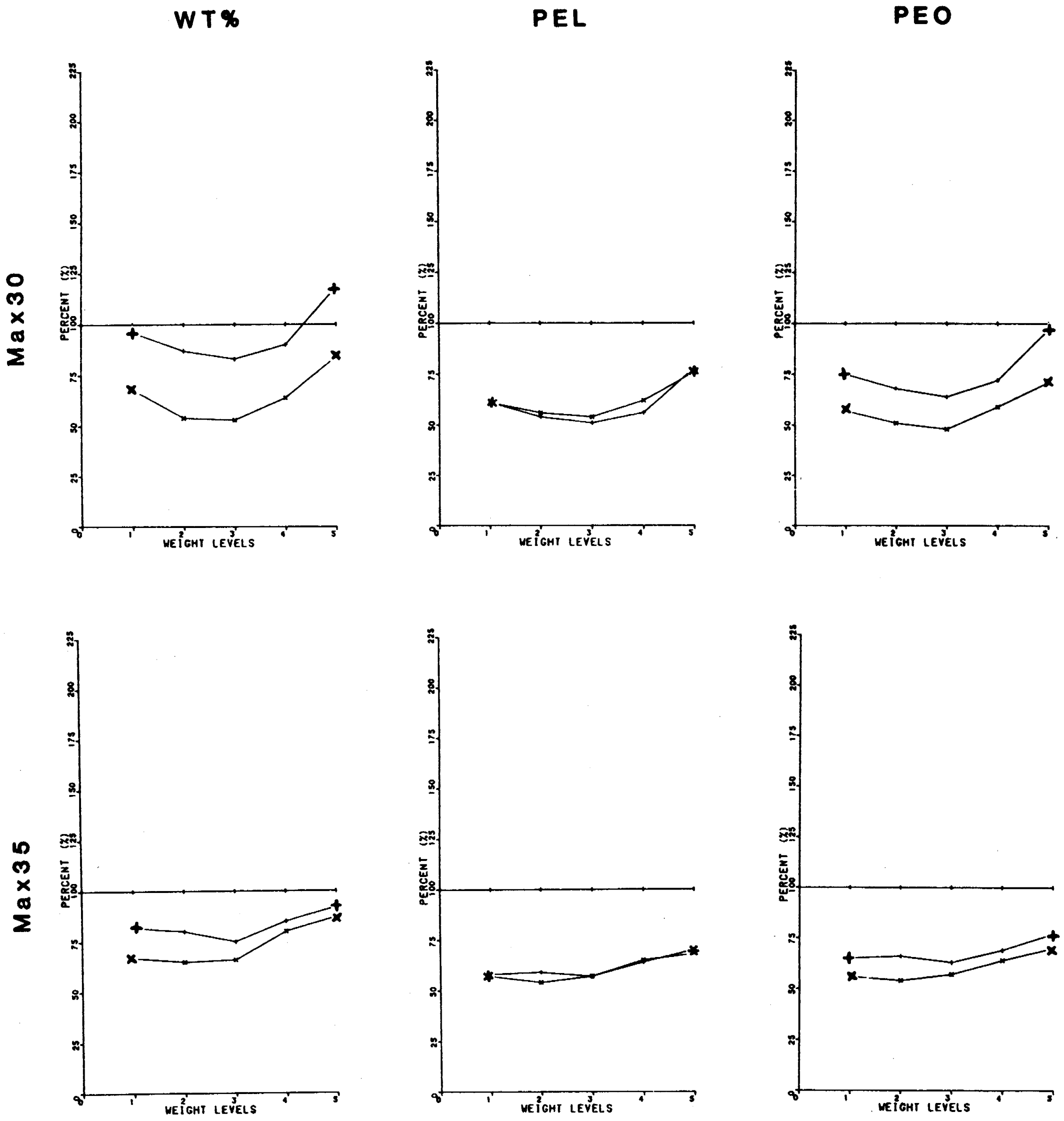

Figure 3. Mean WT% (percentage of weight lifted in pounds), PEL (percentage of effort for lifter), and PEO (percentage of effort for observer) judgments over two scaling conditions plotted by judgment type for the Max30 and Max35 lifters. (The ordinate is percent and represents the range from 0 to 225 by increments of 25; the abscissa is weight levels and represents the range from 1 to 5. A line for 100% is marked across weight levels for reference. Display only = +; display with standard = x.)

ance. A quadratic trend was tested using trend weights of +2, −1, −2, −1, +2. Sums of squares were for Max30 = 9,290 and for Max35 = 736. A flat-then-rising trend was tested using trend weights of −1, −1, −1, 0, and +3. Sums of squares were for Max30 = 12,214 and for Max35 = 2,716. In both cases, the flat-then-rising trend accounts for a larger portion of the variance.

The second issue addressed in this experiment was scaling. As in Experiment 1, the essential form of all judgment curves is invariant across both scaling conditions and judgment types, indicating that whatever basis there is for scaling, the relative range of the kinetic values is available in the kinematic form itself. Adjustments in the position of judgment curves relative to one another occurred over the addition of a standard as a basis for scaling. In ANOVA, the scaling factor was significant, $F(1, 11) = 11.91$, $MS_e = 3568$, $p < .006$. Judgment was significant, $F(2, 22) = 11.29$, $MS_e = 3703$, $p < .001$; however, the scaling by judgment interaction was also significant, $F(2, 22) = 14.52$, $MS_e = 880$, $p < .001$. In Figure 3, curves for the three judgments squeeze together over scaling conditions.

To reveal whether each judgment type was affected by scaling condition, a repeated measures analysis of variance was performed for each judgment (WT%, PEL, PEO) with weight level, repetition of weight levels, lifter, and scaling as factors. Once again, lifter was not significant and accounted for none or almost none of the variance in all judgments. Scaling was significant for weight judgments, $F(1, 11) = 16.30$, $MS_e = 2932$, $p <$

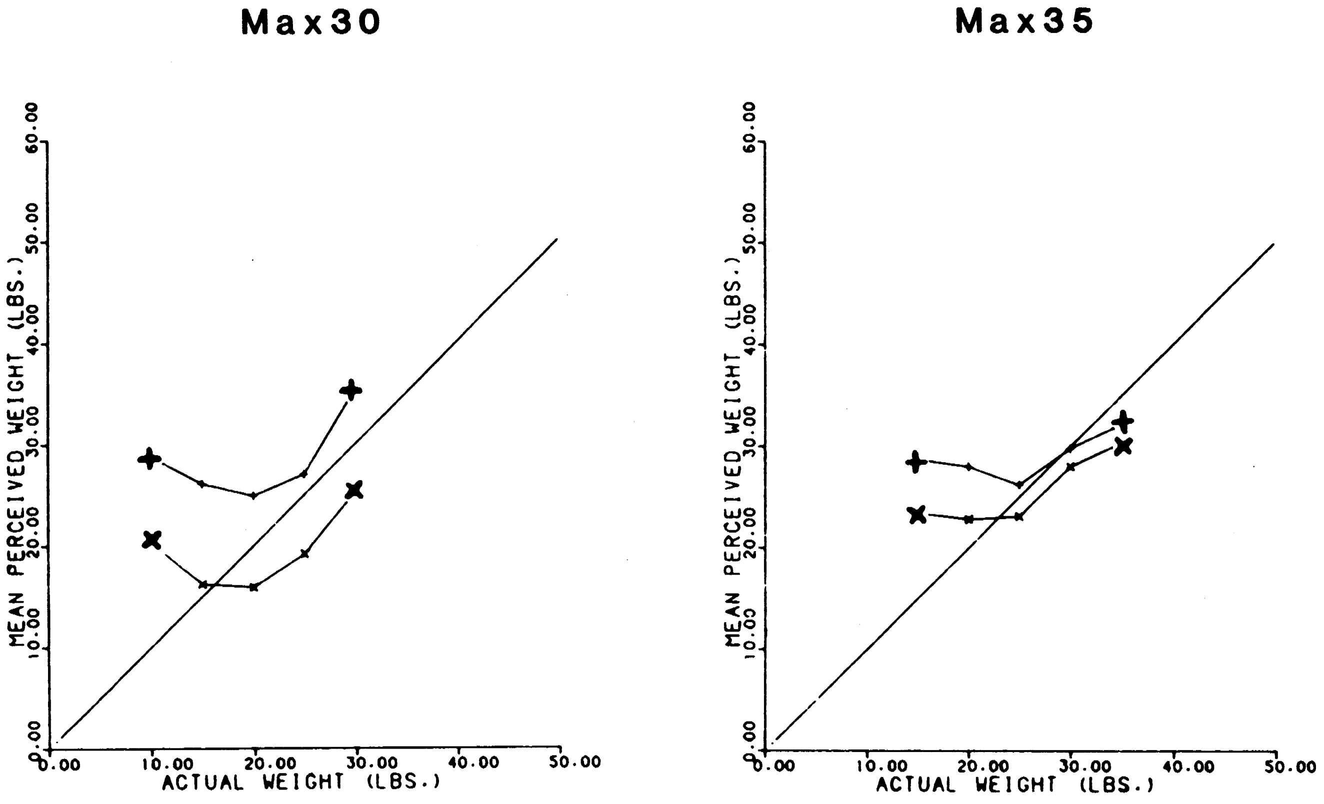

Figure 4. Mean weight judgments versus actual weight over two scaling conditions for the Max30 and Max35 lifters. (Display only = +; display with standard = x.)

.002, accounting for 14.96% of the total sums of squares. Scaling was significant also for PEO judgments, $F(1, 11) = 10.23$, $MS_e = 1981$, $p < .009$, accounting for 6.19% for the total sums of squares. However, scaling was not significant for PEL judgments, accounting for almost none (0.01%) of the total sums of squares.

The trend over scaling conditions for each judgment type is apparent in Figure 3, where judgments are graphed by judgment type over scaling conditions. Both WT% and PEO judgment curves move downward over scaling conditions, whereas PEL judgment curves remain invariant. PEO curves are scaled more accurately in the initial scaling condition and thus are affected more weakly by the addition of an extrinsic scaling basis as reflected in the smaller proportion of the total sums of squares for scaling accounted for by PEO judgments. These scaling results replicate those of Experiment 1 and thus likewise indicate that additional bases for scaling provided by the experimenter merely allow judgments based on the displays to be fine-tuned. Judgments using intrinsic metrics are affected less by the addition of an extrinsic scaling basis than are judgments using an extrinsic metric.

The control task was performed to investigate the possibility that scaling effects might be a result of repeated viewings of the same displays, allowing observers, by virtue of practice, to detect better bases for scaling contained in the displays. The results indicate that this is not the case. PEO judgment curves were separated from and did not move toward PEL judgment curves over repeated viewing conditions.

A repeated measures analysis of variance was performed on the data with weight level, lifter, repetition, judgment, and repetition of weight levels as factors. As before, weight level was significant, $F(4, 36) = 27.39$, $MS_e = 333$, $p < .001$, accounting for 11.75% of the total sums of squares. Lifter was significant, $F(1, 9) = 39.33$, $MS_e = 178$, $p < .001$. Judgment was significant, $F(1, 9) = 29.48$, $MS_e = 929$, $p < .001$. PEL and PEO curves are separated in both repetitions. Repetition was significant, $F(1, 9) = 8.23$, $MS_e = 692$, $p < .05$. The Repetition × Judgment interaction was not significant.

Because the repetition factor was significant, separate analyses were done for each judgment type to determine whether each was affected over repetitions. Weight levels, lifter, repetition, and repetition of weight levels were entered as factors. Repetition was significant for both PEO and PEL. For PEO, $F(1, 9) = 7.02$, $MS_e = 309$, $p < .05$. For PEL, $F(1, 9) = 7.75$, $MS_e = 467$, $p < .05$. Examination of mean judgments for PEL and PEO in each repetition revealed that curves for both judgment types move upward slightly in parallel over repetitions. I can give no account for this effect. PEL did not exhibit this trend between scaling conditions in Experiments 1 and 2. Otherwise, the curves in the control task are similar to those in Figure 3.

In any case, the judgment curves do not move towards one

Table 2
Linear Regressions on Weight Judgments Versus Actual Weight

Scaling condition	Lifter: Max30	Lifter: Max35
Display only	$Y = 0.30X + 22.53$ $r = .23$ $r^2 = .05$ $p < .05$	$Y = 0.17X + 24.78$ $r = .14$ $r^2 = .02$ *ns*
Display with standard	$Y = 0.25X + 14.33$ $r = .32$ $r^2 = .10$ $p < .01$	$Y = 0.38X + 16.12$ $r = .46$ $r^2 = .21$ $p < .01$

another as reflected in the nonsignificance of the Repetition × Judgment interaction in ANOVA. Thus, it can be concluded that scaling effects produced in Experiments 1 and 2 can be attributed to the addition of bases for scaling as previously described.

The control task aside, the accuracy of the weight judgments in Experiment 2 is shown in Figure 4, where mean judged weight values for the two scaling conditions are plotted against actual weight levels. As indicated by increasing r^2 values shown in Table 2, accuracy does improve somewhat over scaling conditions. Overall, however, accuracy in judging amounts of lifted weight is not very good. This is *not* to say that judgments are entirely lacking accuracy. To the contrary, there is some degree of accuracy in the judgments as shown by results of linear regressions, and thus there must be some informative value in this kinematic property for the judgment of lifted weight. However, accuracy in Experiment 2 is not as good as in Experiment 1. The r^2 values are lower in Experiment 2, and judgment curves are shallower. The difference is obvious especially for light-to-medium levels of weight where inaccuracy increases considerably in Experiment 2. Movements at the shoulder and wrist visible in the displays of Experiment 1 were eliminated from the displays of Experiment 2. The difference in results indicates that movements at these joints constitute useful information for the amount of weight lifted in a one-arm curl.

An interesting difference between the curves in Experiment 1 and those in Experiment 2 in the final scaling condition is that the judgments in Experiment 1 approach 100% effort for the heaviest weight lifted, whereas those in Experiment 2 approach only 70% or 80% effort for the heaviest weight. In Experiment 2 as opposed to Experiment 1, lifters were not allowed to lift weights close to the heaviest weight that they could lift. Rather, the heaviest weights lifted were those that lifters could lift consistently a number of times. Observers on average judged these to be of about 80% effort despite having been instructed to judge 100% effort as the most a lifter could lift consistently in the curls. This result indicates that observers are sensitive to the relative level of difficulty experienced by a lifter in lifting a weight.

Experiment 3: The Kinematic Form Of One-Arm Curls

The kinematic form of one-arm curls was measured and compared, as a source of information about lifted weight, with perceptual judgments from Experiment 2. The kinematics of one-armed curls performed by 2 different lifters with five different amounts of weight were recorded. Position versus time data were collected directly. Subsequently, velocities and accelerations were computed with filtered data. Graphs of velocity versus position and of acceleration versus position were compared with perceptual judgment curves from Experiments 2. The object of the comparison was to discover changes in the lifting motion, as revealed in kinematic descriptions, that correspond to changes detected by observers, as revealed by perceptual judgment curves. In both cases, the changes correspond nonlinearly to changes in the amount of weight being lifted from relatively light weight to the heaviest weight that a lifter is able to lift in the prescribed manner. Correspondence between changes in recorded kinematic forms and changes in perceptual judgment is interpreted as evidence that these kinematic forms are detected by observers and used by them to make the required judgments.

Method

Apparatus. Apparatus designed by the author was built by Lars-Erik Larsson at the Psychology Department of the University of Uppsala, Sweden. The apparatus consisted of a surface upon which the lifter stood while leaning upon a vertical back support. Attached to the back support were a fitted styrofoam head rest and elbow rest. The surface upon which the lifter stood was adjustable for varying lifter height. Approximately ½ m below this surface was an adjustable lever arm fixed at one end to an axis of rotation situated on a plumb line directly below the axis of rotation of the lifter's elbow. The lever arm could be adjusted in length to match the length of the lifter's forearm and hand from the elbow to the knuckle. Standard barbell weights were fitted onto the distal end of the lever arm. The weight levels used were as follows: 4.25 kg (9.37 lb), 6.75 kg (14.88 lb), 9.25 kg (20.39 lb), 11.75 kg (25.90 lb), and 14.25 kg (31.41 lb). A stirrup handle accessible to the lifter's grasp was attached to the lever arm by a rigid rod, which connected to an axle on the distal end. When the lifter was in place, his forearm was parallel to the lever arm, and the whole formed a parallelogram, with the axis of rotation of the lever arm directly below the elbow and the weights attached to the end of the lever arm directly below the hand. This arrangement preserved to good accuracy the physical properties of a normal barbell lift. All axles were very smooth with low levels of friction. The main difference was the absence of the centrifugal force at the elbow created by the rotating weight, a difference deemed not to affect the nature of the one-armed curls performed.

A potentiometer attached to the axis of rotation of the lever arm produced a voltage output proportional to the angular position of the lever arm and thus, due to the arrangement, proportional to the angular position of the elbow. The signal was low-pass analogue filtered (Winter, 1979) with an 8-Hz cutoff and sampled via an A/D board on a PDP-11/45 at a rate of 50 Hz. In addition, the sampling was regularly calibrated for drift in the signal.

Before the data were differentiated to derive velocities, they were filtered using two passes in opposite directions of a Butterworth low-pass digital filter of second order with a cutoff of 5 Hz. The data were filtered in the same way a second time before differentiating for accelerations.

Lifters. Two male psychology students at the University of Uppsala participated in the study as lifters. The first student was 180 cm tall and weighed 70 kg. The second was 186 cm tall and weighed 79 kg. The first participant was moderately experienced in general fitness activities, whereas the second student was somewhat less fit and hence experienced the task as somewhat more difficult overall.

Recording procedures. Lifters were positioned for the lifts and performed lifts in exactly the same manner as described in the recording procedures for Experiment 1. The only difference was that lifters grasped and lifted the stirrup handle of the apparatus rather than an actual barbell. The range of weight included to an accuracy of the nearest 2.5 kg the heaviest weight that the first lifter was able to lift consistently three times in each lift. The first curl of the three in a lift will not be included in this analysis because the conditions of lift were somewhat different than in Experiments 1 and 2. Lifts in Experiments 1 and 2 began with the lifter holding and supporting the weight of the barbell. The lifts in the present study began with the stirrup handle, and thus the weight, sitting on an adjustable support from which it was lifted by the lifter. For the purposes of the present study, the analysis will focus on the second curl as being representative of variations in the kinematics of the three curls in these lifts.

Lifters lifted the five different levels of weight four times each in four random-order blocks, resulting in a total of 20 lifts. The first 10 of these will be used for this analysis. Finally, the range of weight levels was held constant over different lifters rather than being adjusted to each lifter's abilities. The result is that the range fits the first participant as desired, but it exceeds the capacities of the second lifter, leaving only four weight levels inside his range including the heaviest weight that he could lift consistently.

Results and Discussion

Figures 5 and 6 contain phase plane portraits of one-arm curls recorded for the 2 male lifters. These portraits are remarkably regular. They exhibit a marked bilateral symmetry that is slightly stronger for left–right halves than for top–bottom halves. Aside from the initial picking up and setting down of the weight, the lift trajectory follows a very regular and repeatable course, tracing over itself as the cycle of the curls repeats.

The kinematic property detected by observers in this study is revealed in these graphs as a qualitative change that occurs over weight levels in the shape of the orbit constituting the phase plane trajectory of the one-arm curl. As long as the weights are relatively light, the orbit maintains a rounded symmetrical shape. When the weight gets heavy, the top part of the orbit representing the upward motion of the lift shows a flattening. This flattening corresponds to a drop in the peak velocity occurring when the forearm is near or at 90° with respect to the upper arm. At this position, movement directly opposes the action of gravity, and the mechanical advantage of the force opposing movement is greatest.

Angular acceleration versus angular displacement graphs corresponding to the phase plane portraits of Lifter 1 appear in Figure 7. Similar graphs (not shown) were produced for Lifter 2.

The qualitative change in the phase plane portraits associated with the heaviest weight lifted is reflected in the acceleration versus displacement graph by a shallower slope at zero acceleration midway through flexion.

For analysis, various values were picked off of these velocity and acceleration graphs. For the second curl in each lift, these values were plotted versus weight levels for each of the 2 lifters. Figures 8–11 contain graphs for durations, amplitudes, peak accelerations, and peak and average velocities. From inspecting these graphs and comparing them with the perceptual judgment curves of Experiments 1 and 2, it is apparent that the graphs for peak and average flexion velocity and for duration of flexion movement best predict the judgment curves. Amplitudes remain fairly constant over weight levels. Although peak accelerations might vary somewhat with the amount of weight being lifted, the linear form of these curves does not reflect the form of the judgment curves.

These kinematic measures are compared most appropriately as sources of information with the perceptual judgments of Experiment 2 because the displays in Experiment 2 included only movements around the elbow and only full amplitude curls. Independently for each of the 2 lifters in Experiment 3, correlations were performed comparing each of the kinematic measures on flexion movements with PEL judgments for both the Max30 and Max35 lifters from Experiment 2. PEL judgments from the first scaling condition (display only) were used. These are representative of all judgment curves in Experiment 2 because PEL curves remained invariant over scaling conditions and because other judgment curves reflected the form of PEL curves. In Experiment 3, values corresponding to only four weight levels were obtained on kinematic measures for Lifter 2. These values were paired with PEL values corresponding to the highest four weight levels in Experiment 3. Pearson's r values are shown in Table 3. The pattern of correlations supports the hypothesis that the change in kinematic form is the source of information in the displays. *Taken together,* the kinematic measures provide a crude description of the change in kinematic form occurring over levels of lifted weight. These measures must be interpreted heuristically and with care. The nonsignificance of the correlations for peak acceleration, for instance, should not be taken to mean that the behavior of peak accelerations contributes nothing to perceptual judgments. The pattern of correlations provides an indication that the style of change exhibited in the phase plane portraits corresponds to the pattern of perceptual judgments.

No one of the measures used by itself describes the source of information adequately. For three reasons in particular, the source of information would be described insufficiently and incorrectly as a drop in peak velocity. First, the same evidence that might justify a claim for peak velocity also would justify claims for total cycle duration and average velocity, both of which are defined over the entire amplitude of movement. Second, it is not merely the peak velocity that drops but a continuous set of velocities occurring along a continuous subset of positions and dropping by an amount that varies according to a continuous function of position. Use of peak velocity is a heuristic means of describing this drop. Third, and most important, the peak velocity is a relative aspect of the lifting event. It occurs at a specific location along the position and sits in a specific relation to the remaining velocities in the event. The significance for observers of a change in peak velocity cannot be evaluated on the evidence independent of either its location of occurrence or its relation to remaining velocities. Further, the relative nonchange of extension velocities as well as flexion velocities near amplitude endpoints can only be assumed to contribute equally to the significance of the displays as does a drop in velocities in the neighborhood of midflexion. There is no evidence on which to base a claim for the unique perceptual significance of a restricted and isolable portion of the lift trajectory. The claim that a change in kinematic form constitutes the source of information is the more conservative hypothesis, given the evidence, despite its novelty. A more appropriate measure of

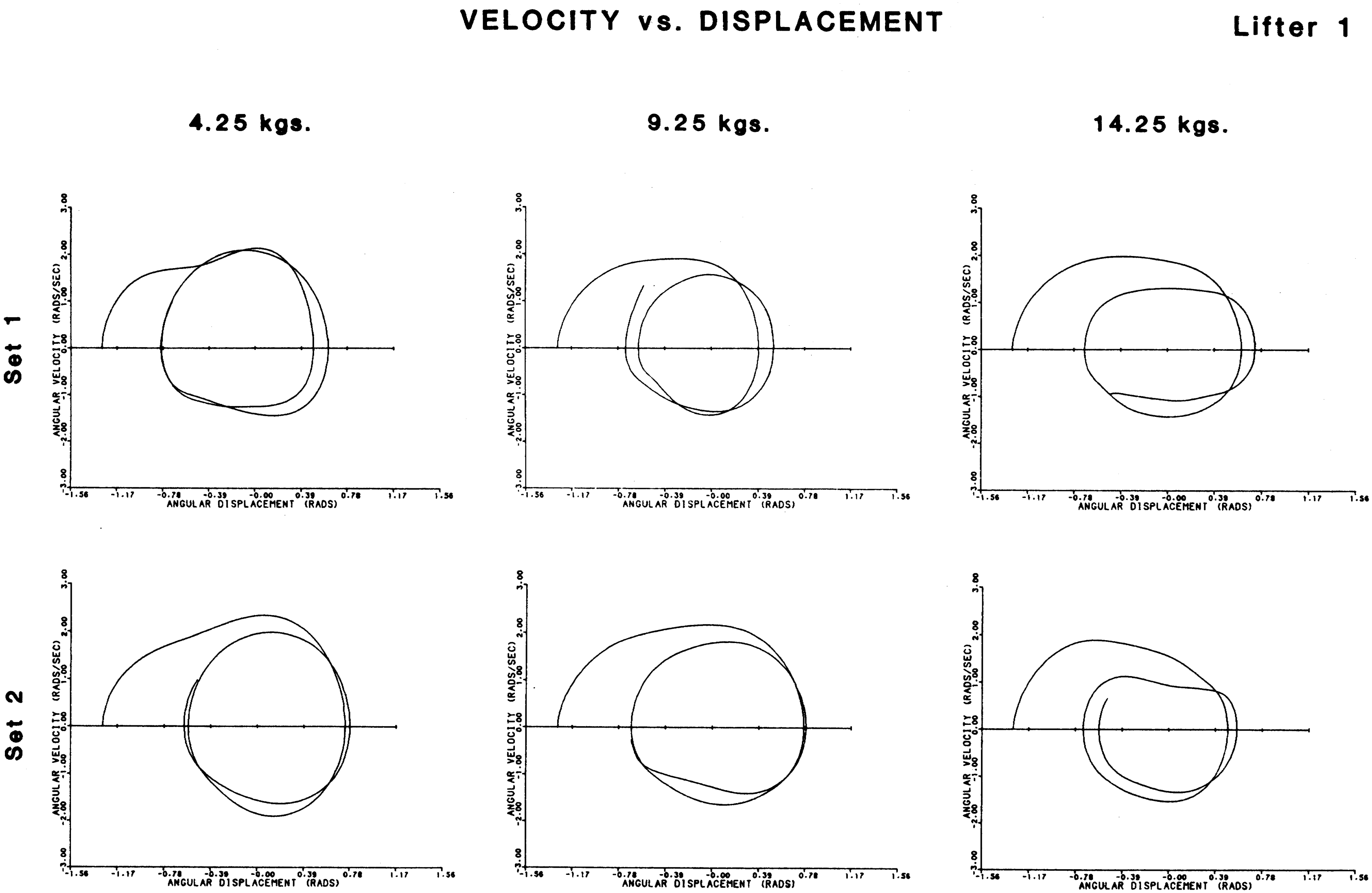

Figure 5. Two sets of phase plane portraits of one-arm curls performed by Lifter 1. (Three of the five weight levels are shown. Ordinate = angular velocity from −3 to +3 radians per second. Abscissa = angular displacement from −1.56 to +1.56 radians. The origin for angular displacement corresponds to a 90° angle between upper arm and forearm. Positive velocity signifies elbow flexion.)

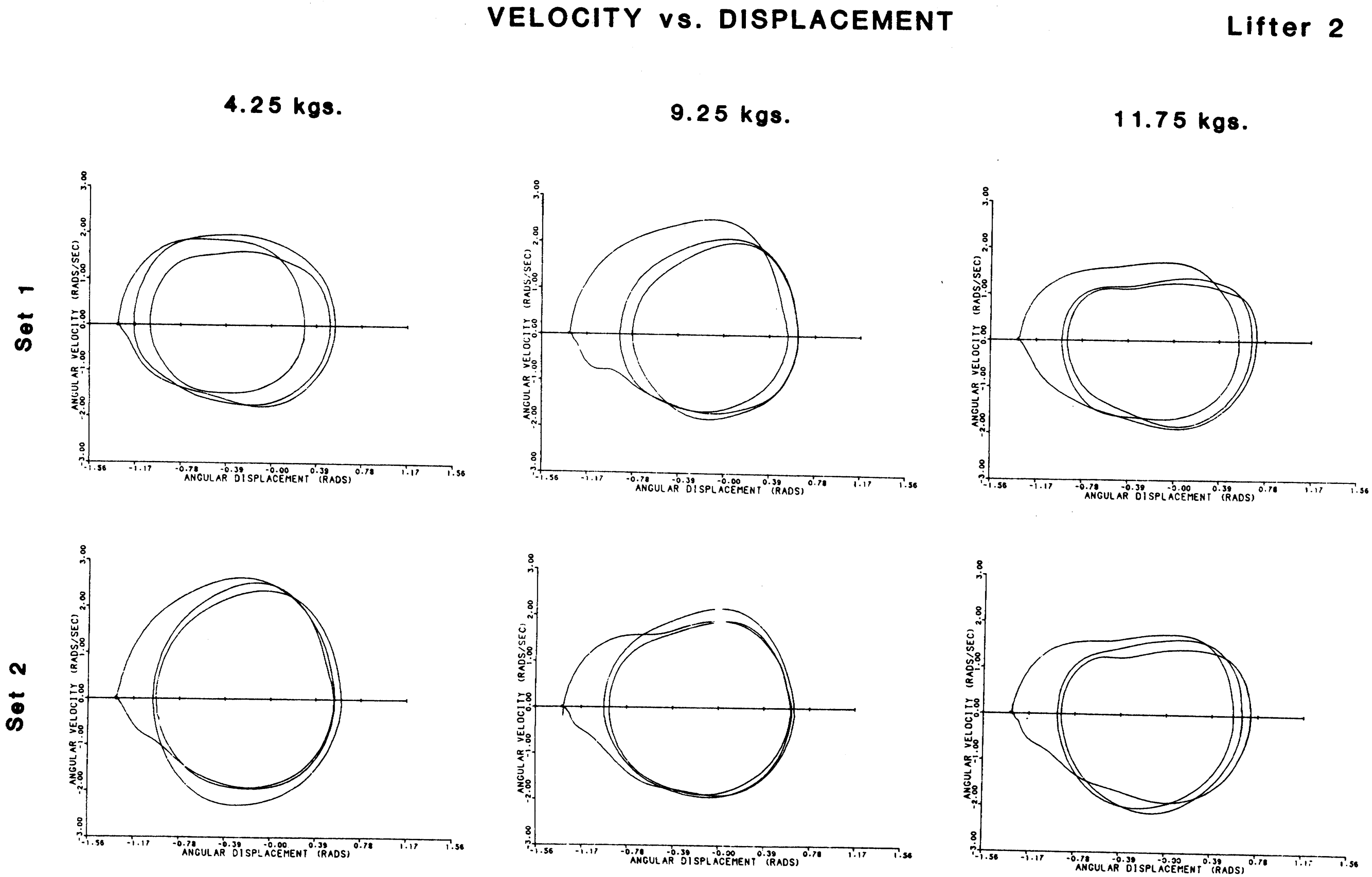

Figure 6. Phase plane portraits of one-arm curls performed by Lifter 2. (Three of four weight levels are shown. Ordinate = angular velocity from −3 to +3 radians per second. Abscissa = angular displacement from −1.56 to +1.56 radians.)

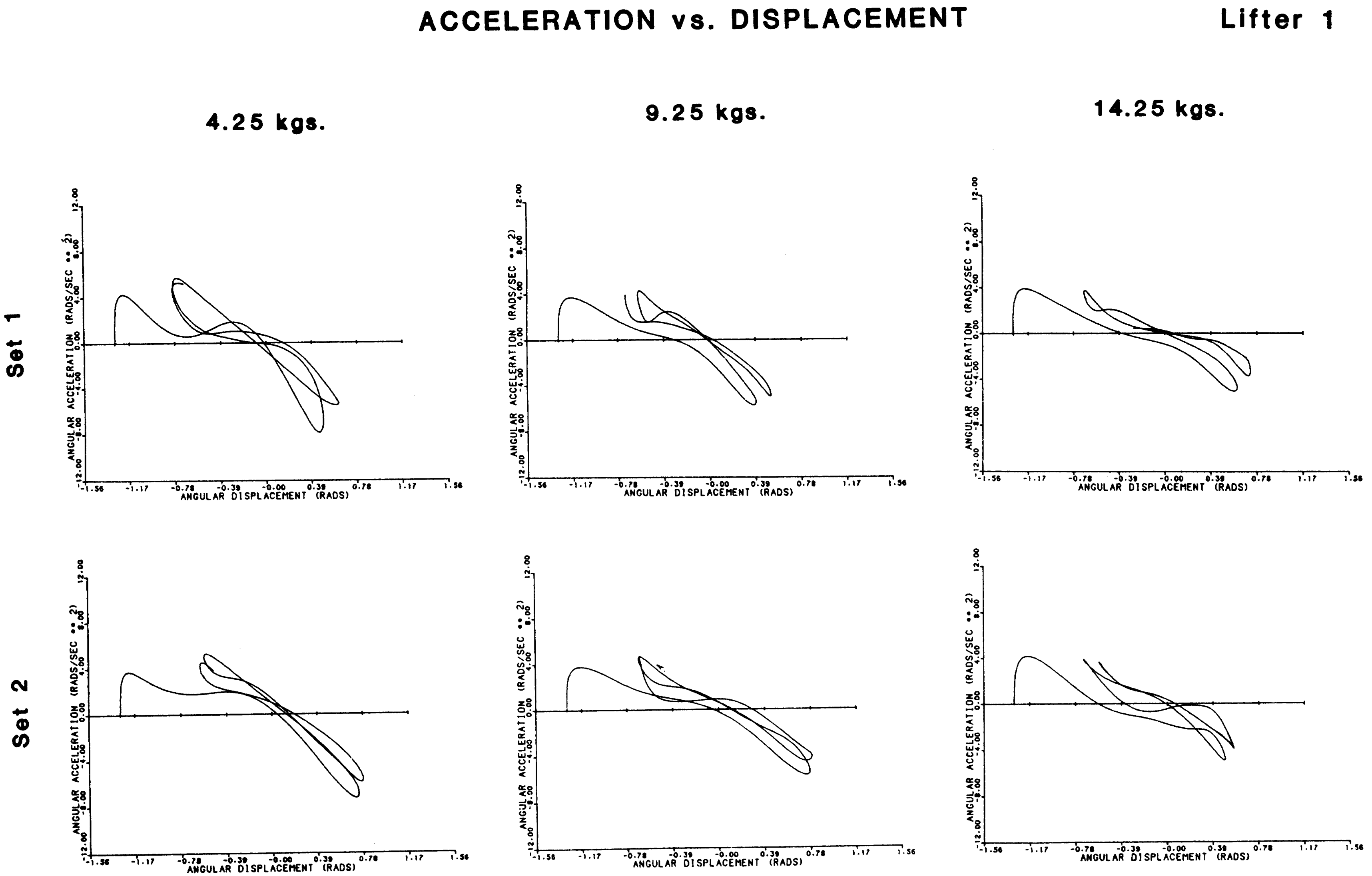

Figure 7. Angular acceleration versus displacement plots corresponding to phase plane portraits in Figure 5. (Ordinate = angular acceleration from −12 to +12 radians per second squared. Abscissa = angular displacement from −1.56 to +1.56 radians. For acceleration, sign signifies both direction of movement [+ = flexion; − = extension] and type of acceleration [+ = acceleration; − = deceleration]. Following the plot trajectory, positive acceleration signifies accelerative flexion. Crossing the axis, negative acceleration reflects decelerative flexion. On the return, negative acceleration corresponds to accelerative extension. Crossing the axis, positive acceleration corresponds to decelerative flexion. Then the cycle repeats.)

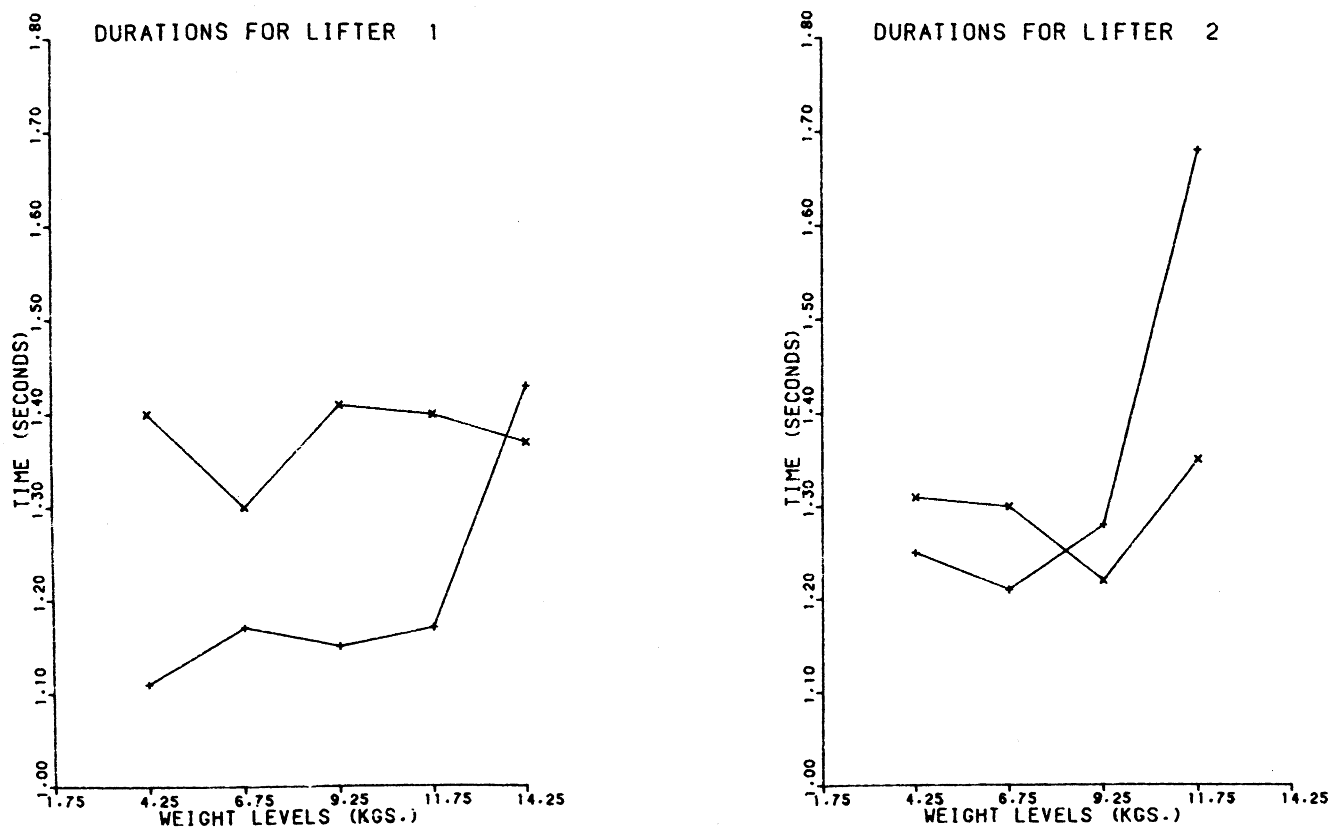

Figure 8. Durations for one-arm curls versus weight levels for Lifters 1 and 2. (The ordinate is time, in seconds, and represents the range from 1 to 1.80 by increments of 0.10. The abscissa is weight levels, in kilograms, and represents the range from 1.75 to 14.25 by increments of 2.50. Flexion = +; extension = x.)

change in kinematic form remains to be developed, probably within the domain of differential geometry.

General Discussion

These experiments simultaneously investigated two questions that emerged from the results of Runeson and Frykholm (1981). In that study, observers accurately judged amounts of lifted weight from the complex kinematic patterns of full body lifts. The first question was what properties of these kinematic patterns allow judgments of weight to be made. The present experiments explored the informative value of patterns of variation in velocity of the lifted object over position. The results of Experiment 2 showed that a 1-*df* lift trajectory allowed observers to distinguish amounts of lifted weight to a very limited degree. This aspect of the full body lifts performed in Runeson and Frykholm (1981, 1983) could not have been the primary source of information for lifted weight, given the comparatively superior performance of Runeson and Frykholm's observers. Observers in the present study were best able to discriminate amounts of weight approaching the maximum that a lifter was able to handle in the constrained one-arm curl. Kinematic recordings in Experiment 3 revealed that the pattern of variation in velocity in the one-arm curls did not vary significantly over light-to-medium levels of weight. However, heavier weights produced a characteristic flattening of the phase plane portrait. This flattening corresponded to a drop in velocities occurring in the neighborhood surrounding half-amplitude of flexion together with a lack of change in velocities at remaining positions of both flexion and extension. The results indicated that observers were able to detect this change in the lift trajectory. However, observers' judgments reflected more than an ability to detect changes in kinematic patterns. The judgments of weight indicated that variations in kinematic properties of a patch–light display were scaled somehow to enable observers to judge values of a kinetic property.

The second question emerging from Runeson and Frykholm's study concerns the basis for this scaling. The results of Runeson and Frykholm (1981) demonstrate that some basis for scaling judgments of weight must exist in the kinematic patterns of the displays themselves. The standard provided by the experimenters might have allowed absolute-interval scaled weight levels to be scaled to zero, but it could not have bridged the gap between ordinal and ratio scaling. The present experiments investigated the efficacy of the scaling basis intrinsic to the displays, and the contribution to accuracy[7] of judgment of an addi-

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[7] When evaluating the efficacy of perceptual information, it is important to note that accuracy is an inherently functional notion. Measured

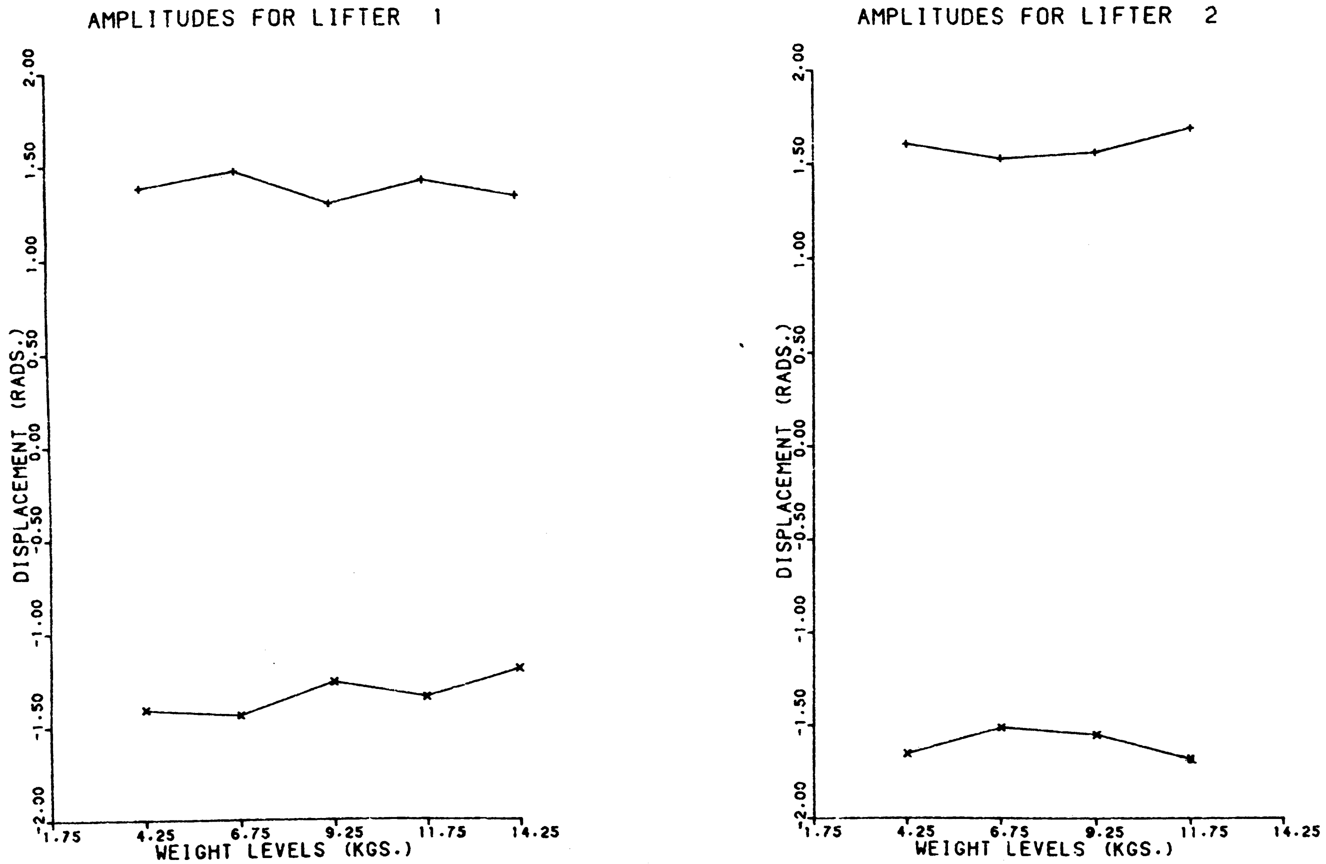

Figure 9. Amplitudes for one-arm curls versus weight levels for Lifters 1 and 2. (The ordinate is displacement, in radians, and represents a range from −2 to +2 by increments of 0.50. The abscissa is weight levels, in kilograms, and represents a range from 1.75 to 14.25 by increments of 2.50. Flexion = +; extension = x.)

tional basis for scaling provided extrinsically by the experimenter. The results confirm that the kinematics of the displays provide the primary basis for scaling judgments of lifted weight. Relative interval scaling was determined by the displays. The form of the judgment curves determined in the display-only conditions remained essentially unaltered in successive conditions, which included an extrinsic standard. Slight changes that effectively smoothed out a couple of the curves in Experiments 1 and 2 might be attributed to practice at detecting fairly subtle changes in the kinematics of light-to-medium weight levels.

Absolute interval scaling was determined primarily by the displays, with slight adjustments sometimes occurring with the addition of an extrinsic standard. The results of Experiment 1 exhibit an interaction between the range of weight judgments and the distance of the entire range from zero. Decreases in judged weight values over scaling conditions were accompanied by a compression of the judged range, leaving relative scaling intervals unchanged. However, the results of Experiment 2 reveal no such effect. The slopes of judgment curves in Experiment 1 were greater than those in Experiment 2, contributing to the greater overall accuracy of judgments in Experiment 1. The lack of an interaction between slope and height of curves over scaling conditions in Experiment 2 might be related to the overall shallowness of the curves. The inability of observers to discriminate light from medium weight levels appears to have overridden any tendency for a decrease in slope to accompany a drop in the entire curve.

Finally, the scaling of distance from zero was determined to a degree by the displays. All judgment curves in the display-only condition fall within a restricted distance from points of perfect accuracy. Subsequent provision of extrinsic scaling bases further restricts this distance.

The judgment curves are reliably nonlinear in Experiment 2 despite linear variations in the amount of lifted weight. This result might seem anomalous for the KSD hypothesis. However, this is not the case. The key to understanding this lies in the following observations. The relation between the curvilinear

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values may vary within a tolerance region without affecting acceptable performance in a task in which the information is used. Variations in functional requirements can alter tolerances determining accuracy. In the present study, only variations in relative accuracy can be considered where the tolerances employed are determined by laboratory conditions. Ultimately, the accuracy of perceptual information should be measured against naturally occurring functional requirements.

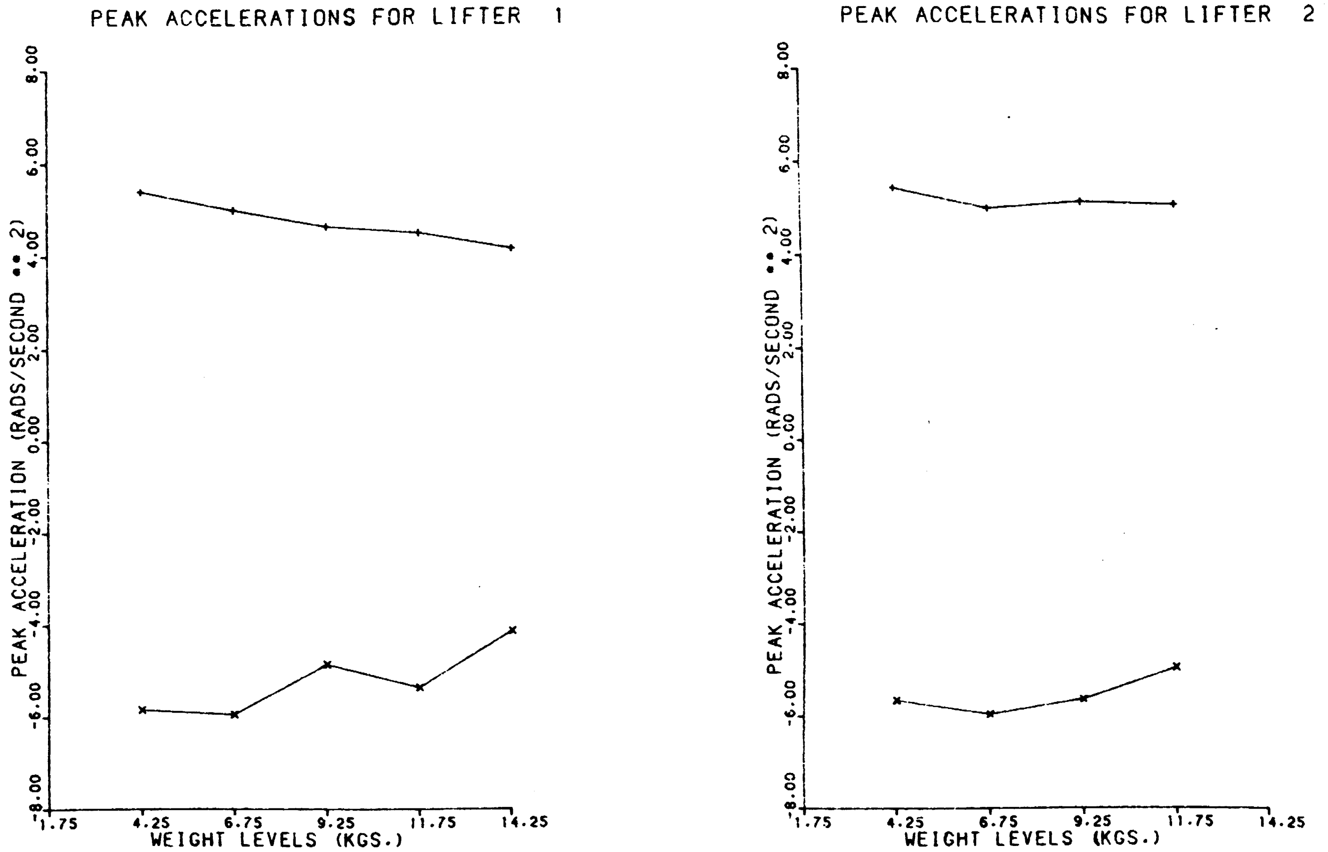

Figure 10. Peak accelerations for one-arm curls versus weight levels for Lifters 1 and 2. (The ordinate is peak acceleration, in radians per second, and represents a range from −8 to +8 by increments of 2. The abscissa is weight levels, in kilograms, and represents a range from 1.75 to 14.25 by increments of 2.50. Flexion = +; extension = x.)

trend in judgments and the strictly linear trend in weight variations reflects a nonlinear relation between variations in the event kinematics and the parametric variations in the particular dynamic factor of interest. The lifted weight is only one of the dynamic factors contributing to the form of the lifting event. Its relation to and manner of interaction with the remaining factors determine the relation of lifted weight to the event kinematics and, thence, to perceptual judgments.

KSD is not a claim that there is always a unique relation between kinematics and dynamics, nor does the validity of KSD depend on such a claim. KSD says that *if and when and to the extent that* there is a unique relation between kinematics and dynamics, *then* kinematic patterns provide a source of information for dynamic properties of an event. Event kinematics are limited as a source of information just to the extent that the relation between kinematics and a dynamic factor in an event is not unique.

In general, unique relations can be expected to obtain only between *resultant* dynamic factors and their kinematic effects. One of the main principles underlying the Newtonian approach is that a collection of forces acting to produce specific motions in an event can be represented in terms of the action of a single resultant force. Proceeding inversely, only the resultant can be distinguished in the kinematics unless the contributions of component forces are distinctive and fail to cancel. For instance, independent characteristics of the motion of a damped oscillator (e.g., a pendulum) reflect the contributions of the conservative force (e.g., gravity) and the dissipative forces (e.g., air and hinge friction) (Thomson, 1972). Gravity keeps a pendulum oscillating in a smooth, symmetric, and periodic motion while friction successively reduces the amplitude of oscillation. Parametric variation in the amount of friction results in proportional characteristic changes in the kinematic trajectory, that is, changes in the degree of decrease in amplitude.

In contrast, simultaneous proportional variations in two dynamic factors can result in kinematic invariance. Increasing the mass attached to a nonlinear spring hanging in the gravitational field can alter its oscillatory trajectory, making it increasingly asymmetric. However, increases in mass can be cancelled by substituting a spring that is stiffer in proportion and identical in other characteristics. The result of proportional parametric variations in stiffness is a trajectory that is unchanged by parametric variations in mass.

In the one-arm curls, increases from light to medium amounts of weight were met by proportional increases in the stiffness of the actuators. The result was an invariant kinematic

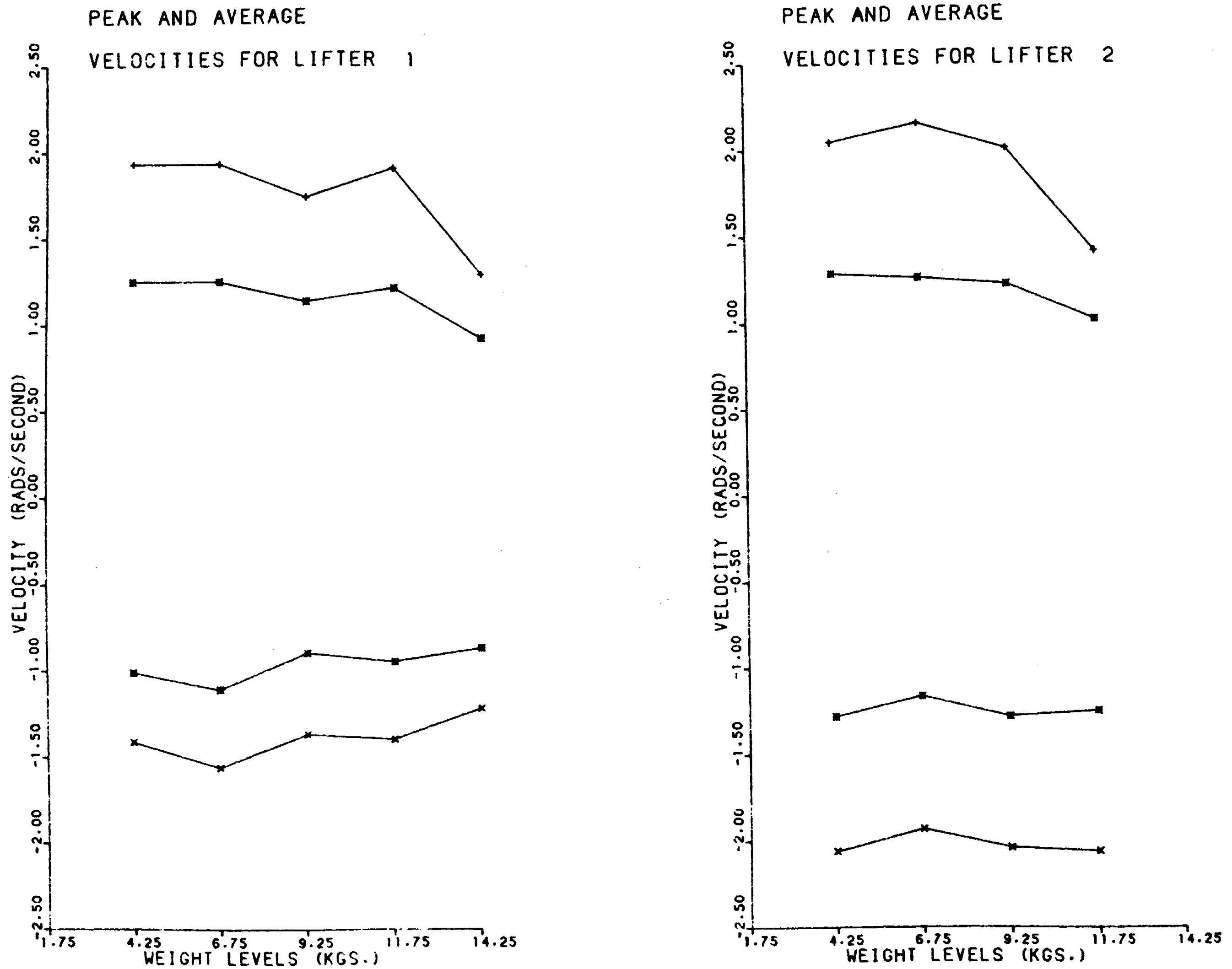

Figure 11. Peak and average velocities for one-arm curls versus weight levels for Lifters 1 and 2. (The ordinate is velocity, in radians per second, and represents a range from −2.50 to +2.50 by increments of 0.50. The abscissa is weight levels, in kilograms, and represents a range from 1.75 to 14.25 by increments of 2.50. Peak velocity, flexion = +; peak velocity, extension = x; average velocity for flexion and extension = *.)

form and thus no source of information for the variation in weight. However, as weights became heavy, velocities in the neighborhood of midflexion dropped while remaining velocities did not change.

Table 3
Correlations Between PEL Judgments and Kinematic Measures on Flexion

Subject	DUR	PK VEL	AV VEL	PK ACC	AMP
Lifter 1	.84**	−.76*	−.75*	−.53	−.23
Lifter 2	.90**	−.91**	−.90**	−.22	−.81*

Note. DUR = duration; PK VEL = peak velocity; AV VEL = average velocity; PK ACC = peak acceleration; AMP = amplitude.
* $p < .05$. ** $p < .01$.

To what might the reduction in velocities at midflexion of the lifts with heavier weights be attributed? The system appears to preserve a preferred trajectory over changes from light to medium amounts of lifted weight. With an invariant velocity profile, increased amounts of weight represent increased power requirements. Eventually, increases in weight must exceed the power capabilities of the system at midflexion, where the lever arm of the lifted weight reaches a maximum, creating a maximum resisting torque. As a result, midflexion velocities must be reduced to allow requisite force to be applied. The system is compelled by power limitations to move down the force–velocity curve to achieve required force levels. (See McMahon, 1984, p. 15 for a graph of the force–velocity relation and accompanying power output.) The velocity reduction means that the muscles are producing high force levels for extended periods of time. The result is increased fatigue. Thus, the change in the kinematic form of one-arm curls is attributable to a specific property of the actuators in human movement, namely the force–velocity relation.

The limitations of power output by limb muscles provide some account for the type of change that occurs in the kinematic form of lifts. The pattern of change maps well to the pattern of perceptual judgments. However, scaling of judgments depends on the perceptual significance of the kinematic change, and this is determined entirely by the perceptual significance of the kinematic form undergoing change. The kinematic form is exhibited in the displays from Experiments 1 and 2, which are readily recognized as human weight lifting. This fact is consistent with the finding that the trajectories recorded in Experiment 3 are characteristic of human limb motion in general. Velocity profiles similar in shape to those recorded in the lifts have appeared in numerous studies of human limb motion involving either one or two joints and varying in amplitude, duration, direction, required accuracy of final position, and limb movement through a unidirectional reach or oscillation along some path (Abend, Bizzi, Morasso, 1982; Atkeson & Hollerbach, 1984; Cooke, 1980; Freund & Budingen, 1978; Gachoud, Mounoud, Hauert, & Viviani, 1983; Hogan, 1984; Jeannerod, 1981, 1984; Kelso, 1984; Kelso, Holt, Kugler, & Turvey, 1980; Kelso, Holt, Rubin, & Kugler, 1981; Lestienne, 1979; Morasso, 1981, 1983; Mounoud, Mayer, & Hauert, 1979; Slote & Stone, 1963; Soechting & Lacquaniti, 1981). That velocity profiles like these contribute strongly to the recognition of human motion is indicated by Johansson's result showing that observers can distinguish patch–light people from patch–light stick figure puppets in under half of a second (Johansson, 1976). However, the peculiar characteristics of the trajectories that enable such peremptory recognition remain to be revealed.

Unique kinematic characteristics of human motion are generated by the unique and extremely complex dynamics of human action. Unfortunately, the dynamics underlying human limb motion is not yet well understood. There is considerable evidence that mammalian movement is organized so that gravity or the elastic components of the actuators can be used to store mechanical energy and return it, thereby reducing metabolic energy consumption (Cavagna et al., 1977; Fedak et al., 1982; Heglund et al., 1982; Hof et al., 1983; Taylor, 1980). For instance, walking is organized as a combination of inverted and upright pendulums (Alexander, 1977; McMahon, 1984; Mochon & McMahon, 1980), while running takes advantage of the elastic compliance of muscles and tendons (Alexander, 1984; Giovanni et al., 1980; Goslow, Seeherman, Taylor, McCutchin, & Heglund, 1981; Taylor et al., 1980). Such organization produces preferred frequencies that reflect the optimal frequencies at which mechanical energy can be conserved via the particular storage medium (Cavagna et al., 1977; Mochon & McMahon, 1980). The preferred frequencies of upper limb motion observed in numerous experiments are around 0.8 to 1.00 Hz. (Abend et al., 1982; Hogan, 1984; Jeannerod, 1981, 1984; Morasso, 1981). The stable and regularly reproduced frequencies recorded in the one-arm curls were in this range. Viviani, Soechting, and Terzuolo (1976) discovered the resonant frequency of the forearm actuators to be approximately 0.8 Hz. This circumstance leads naturally to the speculation that the elastic components of the forearm actuators are being employed to bounce the weight up into the lift on consecutive curls. The sharp acceleration peaks occurring at the endpoints of movement would be consistent with this type of organization. The movements of the shoulder accompanying heavier lifts in Experiment 1 provide a further indication that use of passive compliance in the actuators contributes to resulting characteristic forms of motion. Taylor et al. (1980) have found that reorganization of movement occurs when larger, more compliant elastic components are required to store larger amounts of energy in more forceful movements. Shoulder movements would accompany a shift to the longer two-joint muscles spanning the shoulder and elbow. If this type of reorganization is indeed characteristic of more forceful movements, then this would shed light on the superior judgments in Experiment 1. In pilot studies, free-standing lifters performing one-arm curls exhibited yet further reorganization, eventually using their entire upper trunk to help project the weight into a lift. Successive reorganization of lifting movements might be investigated profitably in future experiments on the visual perception of lifted weight.

As should now be clear, the challenge in realizing the KSD thesis as a theory in specific cases lies in describing the scaling relation between kinematic forms and dynamic factors. When event dynamics are described explicitly in terms of differential equations, each dynamic factor is described by a coefficient (or parameter) on a kinematic variable. KSD may be understood roughly in terms of scaling the values of these coefficients. Thinking this way helps to motivate reference to the relation between kinematics and dynamics as a scaling relation. However, it does not contribute much to an understanding of how specific kinematic forms might scale to specific dynamic factors. Mathematically, the generic relation between kinematics and dynamics is too little constrained and too little understood to provide much guidance.[8]

More helpful, perhaps, is the recognition that the ability to judge scaled values of weight is accompanied by the ability to identify the type of event taking place. This observation is relevant certainly to the results for judgments using alternative metrics. Judgments using metrics intrinsic to the event being observed were less sensitive to the addition of an extrinsic basis for scaling. These judgments were scaled better originally. Judgments of effort for the lifter were invariant over scaling conditions. Judgments of effort for the observer adjusted over scaling conditions less than did judgments of weight. The reduced sensitivity to variations in scaling bases might be attributed to the fact that these metrics were based on a scaling property intrinsic to the event being judged. Both metrics focused on the limiting maximum weight value. This value is a property characteristic

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[8] For instance, nonlinear systems have been systematically studied only within the last couple of decades. The uniqueness of the relation between dynamical systems as models and measured kinematics is investigated within dynamical systems theory as the problem of structural stability. This remains an open problem. See the introduction to Abraham and Marsden (1978). Developing descriptions of dynamic factors within a differential equation often involves more than simple scaling of constant coefficients, especially for nonlinear systems. Coefficients often are functions in kinematic variables, and the form of these functions must be discovered before values can be scaled.

of the *particular type of event,* namely, human one-arm weight lifting.

In general, event types relate directly to scale. Restricted scale values are intrinsic to specific types of events. The sizes of gesticulating people and of trees blowing in the wind fall into specifically restricted ranges, respectively (McMahon & Bonner, 1983). The same is true of plodding elephants and scampering mice, falling rain drops and the waves upon a lake. That an ant can be trapped in a drop of water by the surface tension is related directly to the scale of the event. It is the scale-specific nature of event perception that made *The Fantastic Voyage* so fantastic and truly a work of fiction. An understanding of how and when kinematic patterns allow events to be identified would take us a good way toward a solution to the kinetic scaling problem.

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Received February 21, 1986
Revision received August 29, 1986 ■