An informational analysis of absolute judgments of torque*

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Five male Ss participated in seven experiments involving absolute judgments of stimuli selected from a continuum of torque. Experiment 1 required Ss to make judgments on the intensity of 16 stimuli separated by equal intervals. These results were used in the construction of individual scales of equal discriminability. These scales were then used to select the stimuli for the remaining six experiments, in which 6, 8, 10, 12, 14, or 16 stimuli, separated by subjectively equal intervals, were used. An informational analysis was performed to determine the capacity of the kinesthetic system to transmit information derived from the inducement of torque. Maximum values of 1.680, 2.050, and 2.524 bits of information transmitted were obtained when the response was considered the output, and the input variables were, respectively: the stimulus; the stimulus and the S; the stimulus, the S, and the previous stimulus. These results were discussed in relation to information theory and the use of torque information in closed-loop control of movement.

The control of skilled movement under the closed-loop model of human motor behavior depends largely on the capacity of the individual to interpret sensory feedback. This feedback is monitored and used to compare the actual with the intended movement. The kinesthetic sense, with the various dimensions of movement as its adequate stimuli, seems a modality ideally suited to provide this type of sensory information.

Evidence from studies which deprive or distort kinesthetic afference (Chase, Harvey, Standfast, Rapin, & Sutton, 1959; Laszlo, 1966) support the contention that kinesthesia is important to the control of skilled performance. Sensory feedback is central to almost all models of human performance (Adams, 1971; Chase, 1965a, b; Welford, 1960), and a theoretical framework for the feedback nature of kinesthetic afferent impulses has been suggested by von Holst (1954). In that paper, von Holst suggested that response-produced afferent impulses, which he termed "re-afference," are compared with a reference level, or "efferent copy" of the intended movement. Adams (1971) has suggested that a perceptual trace, a conditioned image of previous responses, serves as a

reference level. Under Adams' theory, a memory trace, which is really an S-R bond, causes the response to occur, but the correctness of the response is determined by the comparison of the feedback from that response and the perceptual trace. In terms of either of these closed-loop models, the important factor is the availability of response-produced feedback information. Basic to an understanding of movement control and to whether kinesthesia can be included in models such as those of von Holst (1954) and Adams (1971) is the determination of the capacity of the kinesthetic system to transmit information.

The only reported study which was sought to determine the capacity of the kinesthetic system to transmit information is that by Marteniuk (1971). He was concerned with the capacity of that system to transmit information relative to movement amplitude. Parenthetically, in the light of recent studies by Marteniuk and Roy (1972) and Laabs (1973), Marteniuk was more likely concerned with the capacity to transmit information relative to the terminal location of movement. Marteniuk (1971) reported a maximum value of 2.48 bits and concluded that this dimension of the kinesthetic system was at least on a par with other sensory systems in its ability to supply the central nervous system with sensory information. Thus he sees cues from amplitude of movement as playing a possible role in nullifying error between intended and actual movement.

In terms of the present study, it is necessary to

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consider whether torque is an adequate stimulus for kinesthesia and thus able to transmit information within the kinesthetic system. While there is considerable behavioral evidence to support the notion that resistance to movement can be perceived with a fair degree of accuracy, it has not been considered an adequate stimulus for the kinesthetic receptors per se. However, Howard and Templeton (1966) do consider accuracy of pressure production a type of kinesthetic judgment. Evidence showing the sensitivity of this system was presented by Jenkins (1947), who found a Webers ratio of .06 for the reproduction of resistances of greater than 10 lbs. Shields (1970), on the other hand, obtained a Webers ratio of .04 for active movement of the shoulder for a standard of 45 deg. Another line of evidence demonstrating that force and movement cues can be used for the kinesthetic system was presented by Briggs, Fitts, and Bahrick (1957), who found that both force and amplitude cues significantly affected performance, with amplitude apparently having the greater effect. Considering the above evidence, it would appear that torque can be an adequate stimulus for kinesthesia. However, to date, there is very little evidence pertaining to the characteristics of this particular dimension of kinesthesia and its capacity to transmit relevant information to the central nervous system. The purpose of the study, then, was to determine the capacity of the kinesthetic system to transmit information derived from the inducement of torque.

METHOD

Subjects

Five volunteer male University of British Columbia students who were naive to both the task and the apparatus were paid \$1.50 per hour for their services as Ss.

Apparatus

The apparatus (Fig. 1) was a device which permitted Ss to be presented with different levels of torque and was almost identical to the one described by Henry and Norrie (1968). It consisted of a vertical section of flat spring steel anchored at the bottom. At the top of the steel strip was mounted a wooden handgrip wrapped around with 2.5-cm-thick foam plastic to reduce pressure cues. At the bottom of the same steel strip, but not attached, as an elbow pad that was adjustable to the forearm lengths of the Ss. Linked with the upper end of the steel strip was a calibrated pointer that was displaced by the movement of the steel strip. The extent of the pointer was proportional to the amount of force applied to the handgrip. For this study, the maximum amount of force applied to the steel strip by Ss was 5,776 g, which converted to 202,160 g/cm of torque. At this level of torque, the steel strip was displaced 12 mm. Free-mounted on the upper edge of the hardboard on which were inscribed the calibrations associated with the pointer was a microswitch. S knew he was at a specific level of torque when the pointer closed the microswitch, since this action activated an auditory signal (a high-pitched beep). This signal informed S that he had reached the level of torque E wished him to induce. This entire apparatus was mounted on an ordinary table. A chair and set of industrial ear protectors completed the apparatus.

Fig. 1. Position of S at the apparatus.

Experimental Design

The present study consisted of seven experiments. The first experiment required each S to use 16 different levels of torque, each of which was designated by a number, 1-16. Level 1 was the lowest and was equal to 12,635 g/cm. The other numbers (stimulus categories) consisted of equal intervals of this magnitude with Level 16 equal to 202,160 g/cm. Each of the remaining six experiments required Ss, in a manner similar to the first experiment, to use 6, 8, 10, 12, 14, and 16 levels of torque, respectively. The torque values of each number and for each experiment were derived from the equal-discriminability (ED) scales constructed for each S separately from the data obtained from the first experiment. (See below for description of ED scales.)

The presentation of Experiments 2-6 was randomly ordered for each S. The number of presentations of each stimulus category was determined by the provision that each follow every other category an equal number of times. This meant that for each of 6, 8, 10, 12, 14, and 16 categories, the number of presentations per category was 60, 64, 60, 60, 56, and 64, respectively.

S's Position at the Apparatus (Fig. 1)

Each S was blindfolded, stripped to the waist, and fitted with the industrial ear protectors that reduced extraneous noise, and led into the testing cubicle. This procedure was followed to limit all extraneous cues. S was seated at the chair, which was attached to the floor in a position fixed relative to the apparatus. Ss were instructed not to permit their backs to touch the chair during trials. S's elbow was placed on the elbow pad and his hand on the apparatus handle so that his hand, wrist, and forearm formed a straight line. From this position, S could apply pressure to the handle to induce the required levels of torque. Special importance was attached to maintaining a constant body position.

Calculation of Torque

Torque was calculated as the product of the distance from the point of contact of S's elbow on the pad to the center of the handle of the apparatus and the force required to displace the handle. As the amount of force was proportional to the force required to displace the handle, the amount of torque could easily be calculated for any displacement. Since the variation in Ss' forearm lengths was very small, the calculation of torque was generalized for all Ss to a length of 35 cm.

Learning Trials

Learning trials were provided for each experiment so that S could become completely familiar with the number assigned to each stimulus category within each experiment. On the instruction

"Go," S pushed on the handle until the pointer closed the microswitch and activated the auditory signal. The microswitch was placed by E so that the level of torque required was presented. On hearing the signal, S released the handle and E identified the number which designated the particular stimulus category. This constituted one learning trial. Ss were presented with each of the stimulus categories in alternate ascending and descending series. The first category in each series was randomly chosen to minimize the anchor effect usually associated with the highest and lowest categories in absolute judgment tasks. This procedure was continued until both S and E agreed that further practice would result in no improvement in S's ability to assign the correct number to each stimulus category in that experiment. In no case was the number of ascending and descending series presented less than the number of stimuli which comprised any particular experiment.

Experimental Trials

The procedure for experimental trials was the same as for the learning trials with the following two exceptions. First, stimulus categories within a given experiment were presented in random order but with the constraint that each category follow every other category an equal number of times. Second, upon releasing the handle, S made his judgment on the number associated with the stimulus category that had been presented. The number of the response category used on any trial could be any of the numbers associated with any of the stimulus categories which constituted the particular experiment, i.e., the stimulus category from which he judged the presented stimulus to be. This procedure was then repeated with the next stimulus category. The intertrial interval was 5 sec. S was instructed that he could request a rest at any time. Rest periods were of 5 min duration, and, following each, S was given as many learning trials as he wished before continuing with the experimental trials.

Data Analysis

The independent variable was the number of stimulus categories and the dependent variable the frequency with which each S used each response category within each experiment.

The purpose of Experiment 1 was to calculate an ED scale for each S. The torque continuum was divided into 16 equal units or stimulus categories, and each category was presented 64 times so that every category followed every other category an equal number of times for a total of 1,024 trials. From these data, the ED scales were calculated according to the procedures outlined by Garner and Hake (1951). This process was considered necessary by Garner (1952) because all Ss do not use the same judgmental criteria, and pooling the data without determining how each S uses the reference (stimulus) categories can lead to serious distortion. Further, these authors state that the selection of stimulus categories with the use of ED scales should lead to increased judgmental accuracy and thus maximize information transfer.

In Experiments 2-7, the major analysis was in terms of information transmission. For each experiment, the information transmission was calculated according to Garner (1952) and by the statistical procedures outlined by McGill (1954) and Garner (1962). The input variables were: the stimulus; the stimulus and the S; and the stimulus, the S, and the previous stimulus. In all cases, the output variable was the response to the current stimulus. The purpose of including S as an input variable was to determine the effectiveness of the ED scale in equating the various judgmental accuracies of Ss. If the ED scales effectively reduced these differences, then there would be no additional information derived from a knowledge of this input variable. The inclusion of the previous stimulus as an input variable was to determine the effect the strength of the previous sensations had on the judgment of the current stimulus.

The following symbols are used in the description of the data analysis: HT is the information transmitted; S is the subject; St, the stimulus; R, the response; and P, the previous stimulus variables.

Fig. 2. Mean ED scale values as a function of torque.

For the first analysis (Analysis 1), data from all Ss were pooled and HT between St and R was calculated according to the equation: $HT = H(St) + H(R) - H(St, R)$. Analysis 2 required the computation of HT between S and R with St held constant; i.e., for each stimulus, the frequency with which each S assigned a response category was entered in cells within a S by R matrix, and HT was computed according to the equation: $HT = H(S) + H(R) - H(S, R)$. The HT values for each stimulus category were then summed, and the average value was computed. This value is a measure of the extent to which Ss respond with different response categories to the same stimulus, and, when added to the value obtained for Analysis 1, gives the total amount of information transmitted given a knowledge of both. Analysis 3 involves calculating information transmitted between P and R with St held constant. Essentially, data from all Ss are pooled and for each stimulus the frequency with which each stimulus is designated a particular response category when that stimulus follows each other stimulus, and itself, was assigned to cells within a P by R matrix and HT calculated: $HT = H(P) + H(R) - H(P, R)$. The values for each stimulus were summed and the average value computed. This value gives an indication of the extent to which the additional knowledge of preceding stimulus affects the way Ss respond or adds to the predictability of the response.

RESULTS

Scale of Equal Discriminability

Individual ED scales were calculated and plotted from data collected in Experiment 1 to determine the levels of torque associated with the various stimulus categories for each of the remaining experiments. For practical purposes, only the average scale is presented in Fig. 2. The use of the ED scale can be illustrated by the following example: For Experiment 2, when six stimulus categories were used, the level of torque associated with each of these stimulus categories would be 22,750, 50,540, 78,350, 113,700, 155,400, and 202,160 g cm, respectively

Information Transfer

Information transfer was calculated using each of

Fig. 3. Mean information transfer for each condition as a function of the number of stimulus categories.

St, S, and P as the input variable and the response as the output variable.

HT(St:R). When data from all Ss were pooled and HT between St and R calculated, the bottom curve in Fig. 3 was determined. The maximum HT of 1.680 bits occurs at 16 stimulus categories. Perfect transmission did not occur in any experiment. The average values obtained for Experiments 2-7, when data are not pooled and HT between St and R is calculated for each S, are shown in the bottom curve of Fig. 4.

HT_{St}(S:R). HT between S and R was calculated to determine if different Ss used the various response categories differently. The results are reflected in the difference between the lower and middle curves of Fig. 3. Note that the amount of additional information gained by a knowledge of Ss tends to increase as the number of stimulus categories increases.

HT_{St}(P:R). HT between previous stimuli and response is shown by the difference between the middle and upper curves in Fig. 3. The shape of the upper curve is slightly steeper, which indicates that the amount of information gained from the previous stimulus increases with the number of stimulus categories. Another way to look at the effect of the

Fig. 4. Mean information transfer for amplitude of movement (Marteniuk, 1971) and for torque.

Table 1
Mean Responses to Each Stimulus Expressed in Terms of the Preceding Stimulus (Experiment 2)

Previous Stimulus	Current Stimulus					
	1	2	3	4	5	6
1	1.38	1.92	2.68	3.78	4.50	5.48
2	1.40	2.14	2.86	3.88	4.44	5.48
3	1.46	2.62	3.14	3.86	4.56	5.46
4	2.14	2.46	3.26	4.16	4.70	5.84
5	1.62	2.96	3.22	4.36	5.12	5.88
6	1.86	2.04	3.52	4.34	5.04	5.60

previous stimulus on the judgment of the current stimulus is to determine if a kinesthetic aftereffect (KAE) is present. An inspection of the mean response category assigned to each stimulus when that stimulus is expressed in terms of the preceding stimulus showed that there was a relatively consistent relationship between the response category used by Ss and the intensity of the previous stimulus. Table 1 shows this relationship for Experiment 2.

HT(St,S,P:R)¹. HT from each of the three input variables is summed and is seen as the top curve in Fig. 3. These values are a measure of the predictability of R given a knowledge of St, S, and P.

Distribution of Stimuli. Of some interest is a comparison of HT when the stimulus values are determined on the basis of equal intervals and when they are determined according to the criterion of equal discriminability. For 16 stimulus categories (Experiments 1 and 7), for a stimulus placed according to physically equal intervals, HT is 1.89 bits and when selected according to ED scales, 1.68 bits.

DISCUSSION

The purpose of using ED scales is to render stimuli selected for absolute judgment tasks discriminably equal. Using this scale avoids the distortion inherent in results calculated from data pooled from Ss where each response category is not used with the same frequency. As a result of minimizing judgmental error, information transfer is maximized. Garner (1953) claimed to show this to hold for absolute judgments of loudness. For stimuli selected from ED scales, HT was 1.62 bits compared to 1.53 bits when stimuli were based on equal physical intervals. In the present study, the corresponding values were 1.68 and 1.89 bits. However, in view of the linear character of the ED scale (Fig. 2), it seems unlikely that its use provides any worthwhile advantage, in the present study, over the use of equal physical intervals.

The question of channel capacity is often raised in studies involving information analysis. Channel capacity has been regarded as a measure of the limited nature of the various sensory systems to

transmit information. Note in Fig. 3 that the curves show no tendency to asymptote. This asymptotic phenomenon is considered to reflect channel capacity. In this respect, the present findings are contrary to the findings for other sensory modalities. For instance, Pollack (1952) obtained asymptote at about five stimulus categories for absolute judgment of pitch, and Garner (1953) at a similar level for loudness. For visual interpolation of a marker on a horizontal scale, Hake and Garner (1951) obtained asymptote at about 10 categories. The fact that the present study failed to demonstrate an asymptote presents several points for discussion. Simply viewed, these results suggest that channel capacity occurs at beyond 16 stimulus categories. In the light of the evidence for other modalities, this seems unlikely. However, there are a number of possible explanations. The first is that as judgmental complexity increases, Ss depend more on input variables which are not inherent in the stimulus itself in making their response. In the present study, this can be seen in the additional information transferred by considering the previous stimulus an input variable. This, together with the previous response, separately and interacting, could supply S with more precise information on which to base his judgments. Garner (1962) mathematically defines combinations of input and output variables in such cases.

The second is that information from other than torque cues, like tactile and amplitude of movement cues, was used by Ss to maximize the information on which they base their judgments. It is unlikely that amplitude cues were of any use to Ss in the present study because the maximum distance Ss were required to move the handle of the apparatus was 12 mm. This converts to .29 deg. If this is divided into the 16 stimulus categories used in this study, the resultant values would be very much less than the difference limen for amplitude of movement—.4 deg for passive elbow flexion (Laidlaw & Hamilton, 1937) and 1.42 to 2.13 deg, depending on the extent of shoulder movement used in a study by Shields (1970). In terms of tactile cues, Henry (1953) reported that these cues appear to be unimportant compared to kinesthetic cues, citing the Weber ratio for cutaneous pressure of .136 compared to his obtained ratio of .061 for resistance of movement. Thus, from these studies it would appear that the use of information from amplitude and tactile cues could not account for the rise in HT at the higher levels of stimulus input.

The third relates to information bias. MacRae (1970) points out that HT estimates are likely to be biased on the high side when large numbers of stimulus categories are used. But since MacRae (1970) argues for a decline in *true* HT, it seems unlikely that the rise seen in Fig. 3 can be totally accounted for by information bias. He would suggest

that caution be used in interpreting this rise because of the objections regarding potential bias, particularly in view of the fact that perfect HT was not found in the present study. If the rise in HT with increasing numbers of stimulus categories is the result of bias, and perfect HT occurs at less than six categories, then caution is suggested in interpreting the current finding that asymptote and, therefore, channel capacity was not detected. That is, there exists the possibility that true HT as a function of numbers of stimulus categories exhibits perfect HT up to somewhat less than six categories and then asymptotes, and that the increase noted in the present results reflects the bias effect. Nevertheless, the most likely explanation probably involves a combination of the several factors discussed above.

Marteniuk (1971) is the only study which has used informational analysis to study kinesthesia. In order to compare the present results with those of Marteniuk, the data from the present study were analyzed in a manner similar to that used by that author. In essence, HT between stimulus and response was calculated for each S separately and then averaged (Fig. 4). This procedure differs from that used in the present study, in which the data were first pooled and HT then calculated. As can be seen in Fig. 4, the values for torque are consistently lower than those for amplitude of movement. That torque rises relatively close to amplitude at 16 categories is probably the result of the factors already discussed.

As there is evidence for the existence of KAE, the memory trace for the previous stimulus was influencing S's judgments. The effect would be a reduction in the transfer of information between the stimulus and response. Evidence from Norrie (1969) regarding force reproduction, and Shields (1970) regarding movement reproduction, suggests that error associated with the immediate reproduction of movement is less than that associated with the immediate reproduction of force. For movement reproduction, error was 2.2% for a 45-deg standard, and for force reproduction, it was 17.2% for a 2,000-g standard. It follows, therefore, that the information transfer for movement may be greater than that for force, as Fig. 4 shows. Nevertheless, it is doubtful that KAE can account for all this difference, and it must be concluded that the capacity of the kinesthetic system to transmit sensory information from cues associated with the perception of torque is probably less than that from the perception of amplitude of movement.

There are implications of this conclusion relative to the control of movement. First, the kinesthetic sense can provide information for the discrimination of torque on a similar basis to amplitude, but at a lower level. Second, if this information available to S is thought of as sensory feedback, it will be available for

S to regulate skilled movement. Gibbs (1954, p. 24) suggests that movement "may be regulated by sense data which are always being fed back from a limb." Almost all models of human motor behavior incorporate response-produced feedback as a vital part of monitoring and control functions (Adams, 1971; Chase, 1965a, b; von Holst, 1954; Welford, 1960). Chase, for instance, requires the perception of response-produced afference for the error detection and correction functions of his information flow model; von Holst requires what he terms "re-fference" to compare with efference copy. That torque can provide some information further supports Marteniuk's (1971, p. 76) conclusion that "the inclusion of kinesthesia as a basis for correlating actual output with intended output ... seems warranted."

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NOTE

1. This value is not strictly the sum of $HT(St:R)$, $HT_{St}(S:R)$, and $HT(P:R)$ because the four-term interaction is missing. See Garner (1962), p. 107).

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