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# Constraints on Human Arm Movement Trajectories*

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ABSTRACT The underlying processes in movement organization and control were studied by varying the conditions under which arm movements were made. The three-dimensional movement trajectories of the following conditions were contrasted: pointing to a target with the index finger versus grasping a disk the same size as the target, grasping a fragile object versus a soft resilient object, and grasping a disk either to throw into a large box or place into a tight fitting well. Results showed that the arm trajectories, as represented by the resultant velocity profile of the wrist, varied considerably in their shape with the main factor being when peak velocity was reached as a function of the total duration of the movement. It appeared that when task demands required greater precision, the main deceleration phase of the trajectory was increased in duration. These results do not support a movement production mechanism that has access to an abstract representation of a base velocity profile and that creates trajectories by a simple scaling procedure in the temporal domain. Rather, the results support a view of movement production as relatively specific to the past experience of the performer and the constraints of the task.

RÉSUMÉ Les processus à la base du contrôle et de l'organisation du mouvement ont été étudiés en variant les conditions sous lesquelles les mouvements du bras étaient exécutés. Les trajectoires de mouvement tridimensionnel des conditions suivantes étaient mises en contraste: pointer une cible avec l'index versus saisir un disque de la même taille que la cible; saisir un objet fragile versus un object élastique, mou; et, saisir un disque soit pour le lancer dans une grande boîte soit le placer dans un puits bien ajusté. Les résultats indiquent que les trajectoires du bras, telles que représentées par le profil de vélocité résultant du poignet, varient considérablement dans leur forme avec le facteur principal apparaissant au moment où le pic de vélocité était atteint en tant que fonction de la durée totale du mouvement. Lorsque la tâche requiert une plus grande précision la phase de décélération principale de la trajectoire augmente en durée. Ces résultats n'appuient pas un mécanisme de production du mouvement ayant accès à une représentation abstraite d'un profil de vélocité de base et créant des trajectoires par un procédé d'échelonnement simple dans le domaine temporel. Ces résultats supportent plutôt l'idée d'une production de mouvement comme relativement spécifique à l'expérience passée du sujet et aux contraintes de la tâche.

The organization and control of movement have been investigated by observing the characteristics of movement trajectories over a variety of different tasks (Abend, Bizzi, & Morasso, 1982; Flash & Hogan, 1985; Morasso, 1981; Munhall, Ostry, & Parush, 1985; Soechting, 1984). Trajectory formation refers to the planning and control of the kinematics of movement and, more specifically, is concerned with the path the movement describes in space and with the speed of movement from the initial to the final position in space.

One might argue that the characteristics of trajectory profiles are important

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because if they remain invariant over various task demands, this is support for a movement organization and production mechanism (i.e., an internal representation) that is both general and abstract (Keele, 1981; Schmidt, 1975). Thus, a wide variety of trajectories might be produced by selecting appropriate temporal and spatial parameters. The idea is that for movements of different speed, distance, or load, the movement trajectories, as represented by the velocity profile, could be scaled along one or both axes to show they all belong to a scalar family of curves. In fact, there is considerable evidence to support the idea that trajectory planning might occur in this fashion (Atkeson & Hollerbach, 1985; Flash & Hogan, 1985; Hollerbach & Flash, 1982; Munhall et al., 1985; Soechting, 1984). One consistent finding reported is that movements have bell-shaped velocity-time profiles that can be scaled in both the amplitude and time domains.

However, there are other studies that lead one to question whether planning and control of trajectories can be explained entirely by scalar adjustment to a base velocity form. For example, Soechting (1984) found that arm movements to small targets resulted in peak velocity being attained earlier and the velocity approaching zero faster than movements to a large target. In a finger-thumb pinching task Cole and Abbs (1986) found that many kinematic variables, including finger and thumb peak tangential velocities, varied considerably across trials. What was most significant, however, was that the relatively large spatial variability of the finger and thumb during this task indicated a lower level of planning. As such, organization of finger-thumb movements appeared to be subordinate to the higher level of motor planning which was concerned with producing a consistent finger-thumb contact force. Cole and Abbs concluded that the top level of movement planning may not be exclusively concerned with any single kinematic variable, but may be rather task specific. Consequently, movement planning could depend greatly on the context and conditions in which the movement is performed.

The aim of the present investigation was to vary systematically the movement context in reaching and pointing movements to determine if there is support for the notion of a relatively task specific movement planning and execution process. Another way of expressing this objective is to examine the effects of varying the number and extent of potential arm movement constraints on movement trajectories. A *movement constraint* is defined as a variable that limits the way in which movement can be organized and controlled. Similar constraints may result in similar movement trajectories, which would imply similar organization and control characteristics. In addition, if a variable does represent a movement constraint, then varying its magnitude should give rise to different movement trajectories for the various levels of the constraint and thus reflect the changes occurring at the planning and control levels. As an example, Soechting's (1984) data suggest to us that target size is a movement constraint, in that his smaller target resulted in velocity profiles which were distinctly different from those produced in attaining the larger target.

The concept of a movement constraint is closely tied to the idea that movement organization and control are influenced directly by the context in which a movement is performed. Further, it might be argued that context effects are related to the effects that past experience has on planning and control processes. In this respect the work of Arbib (1981, 1985) is pertinent, where he suggests that movement organization and control are determined by a knowledge of the environment that is far greater than is possible through sensory stimulation. In essence, he postulates that the internal representation of the world, acquired through learning, is a composite of units where each unit corresponds to a domain of interaction whether it be with an object as a whole or some detail of the object. Abbs and his colleagues (Abbs, Gracco, & Cole, 1984; Cole & Abbs, 1986) hold a similar view when they propose that planning of motor tasks may involve considering the motor goal in terms of sensory consequences. Planning of this sort would not only be dependent on learning but would also result in task specific motor control.

The idea that past experience and sensory consequences lead to task specific constraints on movement planning and control processes is empirically testable. In the present investigation we varied the goal of a reaching movement (to point to a target or grasp an object) as well as the required movement extent and end-point precision. In addition, other conditions involved reaching and grasping a light bulb or a tennis ball, and reaching and grasping an object either to throw it into a large container or place it into a tight fitting container. If these variables actually constrain movement as revealed by the characteristics of the trajectories, evidence would be gained for the hypothesis that task specific knowledge, acquired through past experience, affects movement planning and control processes.

## *Method*

*Subjects and Experimental Procedure:* Five right-handed university students participated in the experiment. They sat in front of a table, with their right hand resting on the table.

In the first of three experiments, subjects were asked to point to a target (2 or 4 cm in diameter) by using the index finger to touch the target or to grasp a disk (1 cm thick, and either 2 or 4 cm in diameter) between the thumb and index finger. Both targets and disks were placed 12 cm away from the body directly in line with the median plane of the subject, and the position of the resting right hand was either 20 or 40 cm to the right of the targets or disks. The movements were made from right to left in a straight line parallel to the frontal plane. Subjects were told to move as fast and as accurately as possible for both the pointing and grasping conditions.

In a second experiment, subjects were asked to use their thumb and index finger to grasp a light bulb or a tennis ball and lift it vertically. Both objects had a diameter of 6 cm. In order to ensure that the subject grasped the bulb by the glass sphere, the light bulb was presented with the socket turned away from the subject. The objects and right arm were placed as in the first experiment except a 30-cm movement was required. No instruction was given about the speed of the required movement.

In the third experiment, each trial consisted of a movement broken down into two parts. The first part of the movement was kept constant. Subjects were asked to use their thumb and index finger to grasp a disk (1 cm thick, 4 cm in diameter) placed as in the first two experiments and, as in the second experiment, requiring a 30 cm medial movement of the right hand. The second part of the movement was either to throw the disk into a 20 cm × 40 cm × 15 cm box positioned 15 cm away and to the left of the disk, or to fit it into a 4.1-cm diameter well placed 10 cm to the left of the object. Before each set of trials, subjects were informed of the required second part of the movement. Experimenter's instructions stressed speed and accuracy.

For each experiment the order of the two conditions was as counterbalanced as possible over the five subjects. For each condition, five practice trials and five experimental trials were given to each subject in a blocked fashion so that one condition was completed before the next one began.

*Recording System:* The WATSMART (Waterloo Spatial Motion Analysis and Recording Technique) system provided three-dimensional coordinates by means of software reconstruction (postdata collection) of two sets of two dimensional coordinates.

The subject to be monitored was fitted with four infrared emitting diodes (IREDS). The four IREDS were attached to the subject's right upper limb: one at the tip of the index finger, lateral lower corner of the nail; one at the tip of the thumb, medial lower corner of the nail; and two on the wrist, one above the head of the ulnar bone and the other one 2 cm lateral to the first one. The X and Y positions of each IRED were sampled at a frequency of 200 Hz by two cameras placed at about 50° to each other. The absolute accuracy of each camera over the field of view was 1/200 while relative accuracy was 1/4000. For conditions of the present study, the absolute spatial resolution for the 3D reconstructed data was between 1.0 and 1.5 mm. Each camera was controlled by its own microprocessor which transformed the data into two-dimensional coordinates that were relayed to an IBM-PC. Strobing of the IREDS, collection time, and sampling rate were controlled by the IBM-PC.

*Data Analysis:* For each trial the two-dimensional data recorded by each camera were reconstructed into a single three-dimensional file, which was then filtered at a cutoff frequency of 10 Hz. To minimize distortion of the movement, the program used a second order Butterworth Filter with a dual pass, thus eliminating phase lag.

The results below are based on the wrist IRED, placed above the head of the ulnar bone, which we take as representing the movement of the arm in space. The data were analyzed in terms of the derived dependent measures of movement time (starting with the first detectable movement and ending with contact of the object or the target), peak resultant velocity (highest point on the resultant velocity curve), and time to peak resultant velocity (this allowed calculation of the primary accelerative and decelerative phases of the movement).

To derive resultant velocity, the filtered displacement data from each of the x, y, and z axes were differentiated using the central finite difference technique (see Pezzack, Norman, & Winter, 1977, for validation of this technique). The resultant velocity for a point in time was then calculated by squaring each of the x, y, and z velocities, summing them, and taking the square root of the sum.

Since the WATSMART data are relatively precise (1.0 to 1.5 mm of spatial error and 5 msec temporal resolution), determination of the start and end of each movement was straightforward. We used an interactive program with graphic representation of the nonnormalized resultant velocity profile. For the start of the movement, the intersection of the baseline signal (i.e., before movement began) and the rising signal in the initial velocity phase was used. Specifically, the time of the lowest, nonrepeating velocity value prior to the continuously increasing resultant velocity values was the point used to define start of the movement.

For those movements where the hand was decelerated by the target (i.e., the pointing condition) our resultant velocity plots gave a pronounced decrease from a positive velocity to a zero velocity which we used to define the end of the movement. This method was corroborated with a technique where we had transducers operating a msec accurate clock signalling the start and end of the movement. We found in this case that the derived movement time from the two methods agreed 90% of the time within ±5 msec (the sampling rate of the WATSMART) and very infrequently over 10 msec.

For those conditions where subjects had to pick up an object, we found that the resultant velocity profile was clear in showing a near zero point (many subjects actually never fully stopped their hand while picking up the object) and then a rapid progression away from this point. The intersection of the descending velocity function and the rising function provided the time when the object was reached. A point of interest here is that extensive experimentation

TABLE 1
Means and Standard Deviations (in parentheses) of the Amplitude (mm/sec) of the Peak Resultant Velocity

| Task | Target/Disk Size | Movement Amplitude 20 cm | Movement Amplitude 40 cm |
|---|---|---|---|
| Point | 2 cm | 1077<br>(181) | 1717<br>(262) |
| | 4 cm | 1135<br>(157) | 1940<br>(330) |
| Grasp | 2 cm | 1074<br>(178) | 1738<br>(308) |
| | 4 cm | 1160<br>(209) | 1836<br>(362) |

indicated that examination of the resultant velocity profile was as accurate an indicator of when movement began and stopped as data derived through examination of the velocity profiles of the individual x, y, and z axes.

Other results are shown as time normalized resultant velocity which were obtained by normalizing each trial in the temporal domain to 100 points. It should be noted that the velocity values were not normalized, only the time base. This method was somewhat different than has been used in the past literature (e.g., Atkeson & Hollerbach, 1985; Munhall et al., 1985; Soechting, 1984), where velocity is scaled in relation to the ratio between the maximum velocity of a reference curve and maximum velocity of the experimental curve as well as in relation to the ratio between the distance travelled and a reference distance. As Atkeson and Hollerbach state, this scaling procedure is used because of imprecision in determining movement start and stop points. We did not use this procedure because our system allowed good estimates of these parameters. In addition, our main interest was in the time domain, and our method directly addresses issues in motor control dealing with this domain.

## *Results*

*Pointing To a Target Versus Grasping a Disk:* Four dependent variables were analyzed: the peak of the resultant velocity; the movement time, determined from the first detectable movement to contact with the target or disk; the time of the acceleration phase, from beginning of movement to the peak of resultant velocity; and the time of the deceleration phase, from the peak of resultant velocity to contact with the target or disk.

For all the above mentioned dependent variables, 2 × 2 × 2 ANOVAS with repeated measures were performed. The independent variables were two tasks (pointing, grasping), two movement amplitudes (20 cm, 40 cm), and two target/disk sizes (2 cm, 4 cm).

*Peak Resultant Velocity.* As shown in Table 1, the peak of resultant velocity was very similar for pointing and grasping ($F < 1$) in each condition. Moreover, the movement amplitude, as well as the target/disk width, had similar effects for both pointing and grasping movements. Indeed, the peak of resultant velocity was significantly higher with increasing target/disk width, $F(1,4) = 9.38$, $p < .05$, and with increasing movement amplitude, $F(1,4) = 99.72$, $p < .001$.

TABLE 2
Means (in msec) and Standard Deviations, (in parentheses) of Movement Time (MT), Acceleration Time (AT), and Deceleration Time (DT)

| | | Movement Amplitude | | | | | |
|---|---|---|---|---|---|---|---|
| | | 20 cm | | | 40 cm | | |
| Task | Target/Disk Size | MT | AT | DT | MT | AT | DT |
| Point | 2 cm | 264<br>(52.4) | 174<br>(16.8) | 90<br>(22.2) | 351<br>(77.8) | 232<br>(13.2) | 119<br>(38.4) |
| | 4 cm | 255<br>(33.5) | 170<br>(18.0) | 85<br>(21.5) | 316<br>(66.3) | 222<br>(23.9) | 94<br>(38.7) |
| Grasp | 2 cm | 425<br>(50.4) | 180<br>(18.7) | 245<br>(35.5) | 524<br>(92.0) | 263<br>(33.0) | 261<br>(43.4) |
| | 4 cm | 408<br>(84.7) | 195<br>(44.3) | 213<br>(58.8) | 495<br>(90.8) | 243<br>(45.0) | 252<br>(28.4) |

TABLE 3
Means and Standard Deviations (in parentheses) of the Percentage of Total Movement Time Spent in Acceleration

| | | Movement Amplitude | |
|---|---|---|---|
| Task | Target/Disk Size | 20 cm | 40 cm |
| Point | 2 cm | 66 (10.2) | 66 (12.7) |
| | 4 cm | 67 (5.1) | 70 (11.2) |
| Grasp | 2 cm | 43 (2.3) | 49 (4.6) |
| | 4 cm | 47 (1.8) | 49 (2.6) |

Note. Percentage of movement time spent in deceleration is 100 minus percent time spent in acceleration. The standard deviations of these two percentages are identical.

*Movement Time.* Table 2 shows movement time for pointing and grasping movements as a function of the target/disk width and movement amplitude. The average movement time was significantly longer for grasping than for pointing movements, $F(1,4) = 100.06$, $p < .001$. In addition, there was a similar effect of movement amplitude on pointing and grasping movements: movement time was longer for larger movement amplitude, $F(1,4) = 45.13$, $p < .005$.

It was interesting that for the same movement amplitude and target/disk size, grasping movements took more time than pointing movements, although the size of the peak resultant velocity for these two tasks was similar. In other words, the wrist in both tasks reached the same maximum resultant velocity, but in the pointing task, the hand arrived at the target sooner. This would imply that the proportion of time for the acceleration and deceleration phases for these two tasks were different.

*Acceleration and Deceleration Phases.* Table 2 also shows the times of the acceleration and deceleration phases for each of the conditions. Both phases were

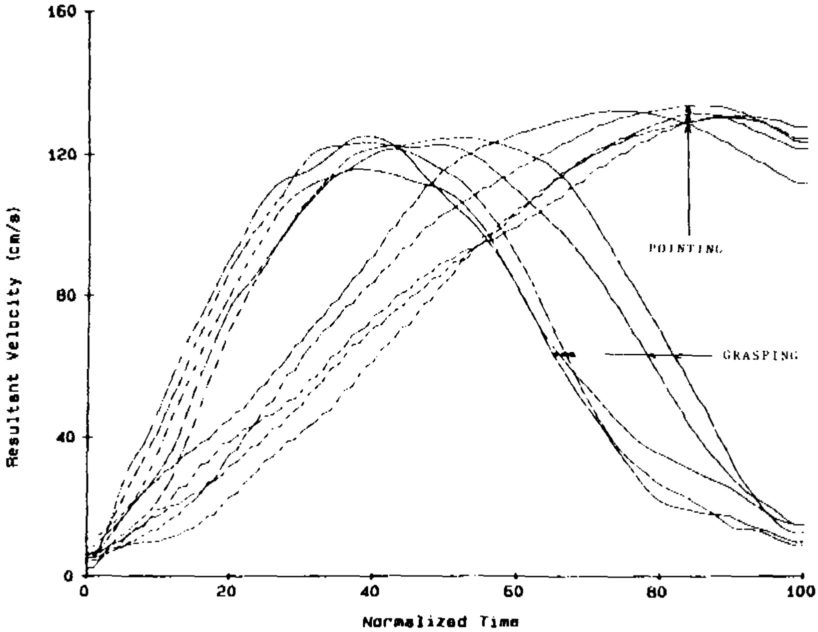

Figure 1. Representative trajectory profiles, normalized in time, for one subject for the tasks of pointing to a target vs. grasping a disk.

significantly longer for grasping movements compared with pointing movements, $F(1, 4) = 7.73$, $p < .05$ and $F(1, 4) = 173.38$, $p < .001$, for the acceleration and deceleration phases, respectively.

It is worth noting that, regardless of the task, movement amplitude had a significant effect on the acceleration phase, $F(1, 4) = 22.76$, $p < .01$, where this phase was longer for larger movement amplitudes. On the other hand, target/disk size had a significant effect on the deceleration phase, $F(1, 4) = 9.54$, $p < .05$, *where the deceleration phase was longer for the smaller target/disk.*

The above results were based on data in real time; now these data will be considered as a percentage of the total movement time. The idea here is to test the notion that for movements performed under the three independent variables of the present study, the movement trajectories could be scaled along the time axis to show they all belong to a scalar family of curves. If this is so, then the percentage of time for the acceleration and deceleration phases should remain constant with respect to each other over the two tasks and the conditions of movement amplitude and target/disk size. Table 3 presents the means of interest.

A significant effect was found for the relative length of the acceleration phase as a function of pointing versus grasping. The percentage of total movement time spent in acceleration was greater for pointing movements than for grasping movements, $F(1, 4) = 41.26$, $p < .005$. Of course, identical statistical results were found for the percentage of total movement time spent in deceleration, in that it was greater for grasping movements than for pointing movements. No other results reached statistical significance.

TABLE 4

Means and Standard Deviations (*in parentheses*) of Movement Time (MT), Velocity (RV), Acceleration Time (AT), Deceleration Time (DT), and Percentage of Total Movement Time Spent in Acceleration (% AT)

| | Grasping | | | | Grasping To | | | |
|---|---|---|---|---|---|---|---|---|
| | Lightbulb | | Tennis Ball | | Throw | | Fit | |
| MT (msec) | 469 | (61.8) | 430 | (49.4) | 423 | (43.5) | 487 | (62.3) |
| RV (mm/sec) | 1444 | (281) | 1471 | (344) | 1461 | (301) | 1341 | (296) |
| AT (msec) | 230 | (25.5) | 225 | (22.6) | 230 | (26.3) | 235 | (18.8) |
| DT (msec) | 239 | (30.9) | 205 | (33.4) | 193 | (32.0) | 252 | (36.5) |
| % AT | 49.1 | (4.5) | 52.3 | (3.8) | 54.3 | (4.4) | 48.2 | (5.4) |

Representative resultant velocity profiles for pointing and grasping are presented in Figure 1. Of interest is the movement trajectory of the pointing condition, where it can be seen that the reason for the relatively long acceleration phase in normal time was that this subject, as well as all other subjects in this condition, allowed the target to decelerate the hand. Apparently for this condition, the subjects did not require a precise approach to the target and could afford, within the limits of accuracy set by the experimenter, to let the target decelerate the hand. It is worthwhile to note that in Figure 1, the velocity profiles of the pointing condition are not shown to return to zero velocity but, rather, show the time and velocity at which contact with the target was made. Inspection of the raw data showed a virtual step decrease to zero velocity; but, if these data (including the step decrease) were filtered, the filter imposed artifacts into the data when encountering the step increase and decrease (a dual pass filter) of velocity. For this reason, the step decrease was eliminated from the data.

On the other hand, for grasping a disk, deceleration of the hand occurred until zero velocity was approximately reached at which point the disk was grasped. Thus, the increased demand of having to grasp an object necessitated a more controlled approach than in the pointing condition and resulted in a longer deceleration phase of the movement trajectory.

Figure 1 also shows quite nicely that this subject, as did the others, showed relatively consistent movement trajectories within a condition indicating planning and control mechanisms capable of consistent movement production. The fact that a change in movement trajectory resulted from a change in the task (i.e., pointing to grasping) also shows these mechanisms to be capable of tailoring movements to the exact demands of the task.

*Grasping a Light Bulb Versus a Tennis Ball:* In this experiment, as well as the next one, four dependent variables were analyzed: the peak resultant velocity, the movement time from the first detectable movement to the actual grasp of the object, the duration of the acceleration phase, and the length of the deceleration phase. For all the above mentioned dependent variables, a $t$ test for repeated measures was calculated.

The peak resultant velocity was similar, whether the subject grasped a light bulb or a tennis ball ($p > .05$). As shown in Table 4, movement time was

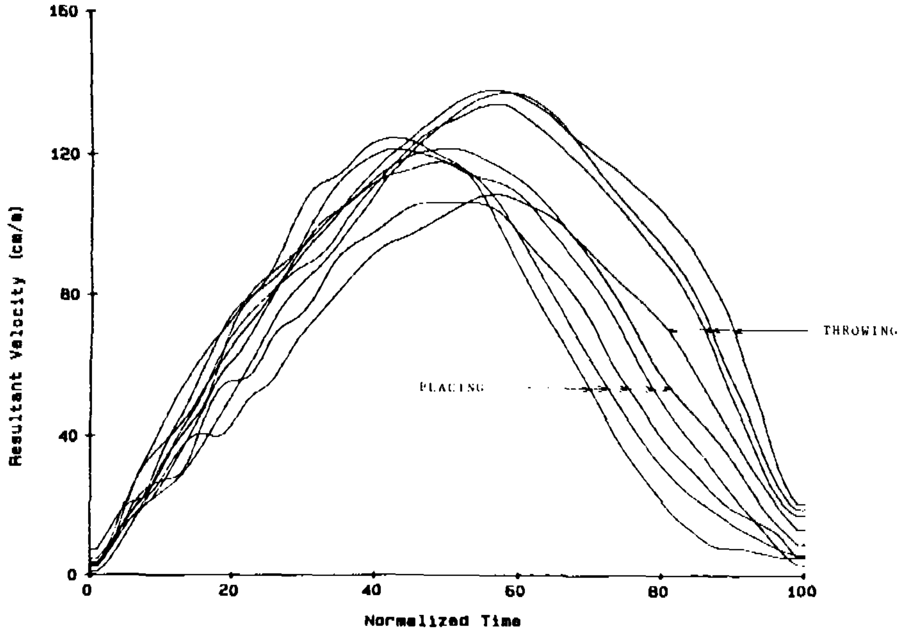

Figure 2. Representative trajectory profiles, normalized in time, for one subject for the tasks of grasping a disk to throw into a large, nearby box vs. placing the disk in a tight fitting well.

significantly longer for grasping a light bulb than a tennis ball, $t(4) = 5.09$, $p < .005$. Since the length of the acceleration phase in real time was similar for the two tasks, the difference in the total movement time was reflected by a significant lengthening of the deceleration phase for the grasping of a light bulb, $t(4) = 2.77$, $p < .05$.

If the acceleration and deceleration phases as derived from the resultant velocity profile are considered as a percentage of the total movement time, no significant difference was obtained between these two variables for either grasping a light bulb or a tennis ball (see Table 4 for the appropriate means).

*Grasping a Disk and Throwing Versus Fitting.* As in the previous experiment, the peak resultant velocity did not show a significant difference in the actual grasping movement as a function of the required task ($p > .05$). In other words, in the grasping movement, the peak resultant velocity was similar regardless of what the subject was asked to do with the disk after grasping had occurred (see Table 4).

As shown in Table 4, movement time was longer for the grasping movement occurring prior to fitting the disk into a well, $t(4) = 3.88$, $p < .01$. This lengthening of the total movement time was reflected in the lengthening of the deceleration phase in real time for this task, $t(4) = 4.08$, $p < .01$, since no significant effect on the length of the acceleration phase was found.

Table 4 also shows that in terms of acceleration and deceleration phases as a percentage of the total movement time, the acceleration phase was longer for the grasping movement prior to throwing the disk, $t(4) = 4.25$, $p < .01$. Conversely, the deceleration phase was longer for grasping the disk prior to fitting it into a well than for grasping prior to throwing.

Figure 2 presents typical resultant velocity profiles for the above two conditions. Apparent is the earlier peak of the resultant velocity for the movement requiring the placement of the disk into the well and, as a consequence, the longer deceleration phase. Also apparent, as in Figure 1, is the relative consistency of the movement trajectories within a condition and the relatively constant difference between the two conditions in terms of trajectory shape. Finally, some comment on the differences in velocity at the point of grasping is in order. As mentioned in the method, in the grasping conditions subjects very rarely fully stopped their hand while picking up the object. As a result, some within-subject between-trials variability in the velocity at the point of grasp was obtained. Figure 2 portrays this variability, and it is of interest to note that all the trials of the condition involving grasping and throwing the disk resulted in larger values of velocity than the trials from the grasp and place conditions. It is as if subjects in the former condition were not as concerned with precisely grasping the disk and thus could afford to "swoop" down and grasp it while the hand was moving relatively quickly.

## *Discussion*

Overall, the data are clear in indicating that the conditions of the present study produced significant differences in the temporal characteristics of the acceleration and deceleration phases of the trajectory associated with arm movement. For instance, movements involved in pointing to a target or grasping a disk produced different trajectories. Remember, the two tasks were equated for information difficulty in that the targets and disks were of equal size and involved movements of identical amplitude. The main difference in the trajectories between these two conditions appeared to be in the deceleration phase; for the grasping task, this phase was longer. Thus, it would appear that the hand movement requirements of a task affect the movement organization and control processes involved in transporting the hand to the object of interest.

The objective of a task was also shown to affect trajectory shape. The data of the third experiment showed that if a subject was required to pick up a disk to place it carefully in a tight fitting well, the deceleration phase of the movement trajectory was disproportionately longer when compared with a movement trajectory produced for a task of picking up the same object but where the objective was to throw the disk into a large box. Thus, it appears as if the intent of what an individual wishes to do with an object affects the movement planning and control processes.

Finally, although the second experiment on grasping a light bulb or a tennis ball did not produce statistically significant differences in terms of the shape of the normalized velocity profiles, there was a significantly longer real-time deceleration phase associated with the light bulb condition (where the acceleration phases of the two conditions were similar) and a similar trend in the normalized data. The trajectory differences observed might reflect the perceived structural stability of the two objects in terms of how they could withstand forces involved in gripping.

Taken collectively, then, these results support the idea that constraints in the form of movement outcome (point vs. grasp), movement intent (to place or throw an object), and object properties (soft ball or fragile light bulb) all affect movement planning and control processes. In terms of the variance of the deceleration phase over the different task conditions, one possible reason for the lengthening of this phase of the movement in certain task conditions might be the requirement for precision. In all three experiments, as the precision requirements of the task increased (i.e., grasping an object as opposed to simply pointing at a target, grasping a fragile object or a durable one, and intending to place an object carefully or simply throwing it without any substantial accuracy requirements), the deceleration phase disproportionately increased. That is, while increases in precision requirements increased the movement time, the duration of the deceleration phase was lengthened disproportionately when compared with the duration of the acceleration phase. One might speculate that these are the results of strategies by the subjects to optimize motor planning and control processes for successful completion of the task. Whether this optimization occurs at the planning or control level is not known. However, we suspect that it may be at both levels. The planning level seems to be affected since the variable of intent influenced trajectory formation, and this is seen to involve a central planning process. On the other hand, the control level also seems to be influenced since the overall results suggest that there was less variability between conditions in the early or acceleration phase of the movement which is more likely to be directly influenced by any central stereotyped movement planning that may be common to all reaching and grasping tasks. Correspondingly, the deceleration phase is more amenable to modification by feedback control processes, and this is where large effects between conditions were achieved.

One notion is that increasing precision requirements of a task may induce subjects to use more sensory information during the movement, and it would be logical that feedback is better used in the homing in or deceleration phase of a reaching and grasping task. This interpretation would be consistent with those studies that have posited that a given aiming movement is broken down into an initial phase that tends to be rather ballistic and gets the hand into the vicinity of the target, and a control phase where there may be one or more submovements concerned with guiding the hand to the target (e.g., Carlton, 1980; Crossman & Goodeve, 1983; Jeannerod, 1984; Soechting, 1984; Woodworth, 1899). Finally, there have been reports of movement trajectories where the deceleration phase has been longer than the acceleration phase (Carlton, 1980; Crossman & Goodeve, 1983; Schmidt, Sherwood, Zelaznik, & Leikind, 1984).

It should be noted at this time that the present results, in terms of the effect of precision on the deceleration phase, extend the work on Fitts's law (Fitts, 1954; Fitts & Peterson, 1964) for serial and discrete movements as well as the work on tracking control (see Poulton, 1974, for a review). This work showed that the precision requirements of a task can be generally described through the effect that the index of difficulty (Fitts, 1954) has on movement time. These effects have been taken as support for increased planning and feedback control of movement necessary to achieve the goal of the task. Our results suggest that an alternative way of operationally defining precision is based on percent deceleration time since, as our tasks became more difficult, this dependent variable systematically increased. In addition to this, however, we extend this previous work by showing that when the accuracy demands (as measured by size of object to be pointed to or grasped) are held constant but where the goal of the task differed (point vs. grasp, grasp a similar sized light bulb or disk, or grasp a disk to throw or place), different movement trajectories are produced. We have recently completed work (MacKenzie, Marteniuk, Dugas, Liske, & Eickmeier, in press) that supports these findings by showing that in a discrete Fitts's task three identical indices of difficulty produced three identical movement times but rather different movement trajectories. In this case, the trajectories were changed in their deceleration phase principally by a decrease in target size even though overall movement time remained constant. Thus, we believe these data, as well as those of the present study, to be important regarding implications for understanding the underlying processes of movement control.

Before going on to discuss the implications of these results, a comment is in order regarding between-condition and within-subject variability. For the most part, our statistical analyses indicated via the numerous significant effects that our between-condition variability was greater than within-condition variability. This speaks well not only for the precision and consistency of our recording technique, but shows that the average of five trials provides for relatively consistent data both within- and between-subjects. Thus, while we did observe some within-subject (over trials) variability (e.g., see Fig. 2 for time to peak resultant velocity and resultant velocity at point of grasp), this variability was not large enough to mask our main finding that percent time from peak resultant velocity changed systematically with precision requirements. It might be argued that the first experiment where we compare pointing and grasping might be an extreme between-condition contrast, in that subjects in the pointing condition allowed the table top to decelerate their limb thus resulting in almost no deceleration phase. However, we are trying to show over the three experiments that the conditions under which subjects produce movements sometimes substantially influence the way in which they plan and control those movements. Taken collectively, we think our results show such influences and, as such, are important for motor control theory in that they offer an alternative view of the movement planning and control process than is now found in the published literature (e.g., Abend et al., 1982; Atkeson & Hollerbach, 1985; Flash & Hogan, 1985; Morasso, 1981; Munhall et al., 1985; Soechting, 1984), which supports the view that over a broad range of movement conditions, velocity profiles tend to be bell-shaped and symmetrical and scale in both the time and velocity domains.

In terms of the implications of the present results for motor control theory, they do not support some generalized motor representation that produces specific movements by a scalar adjustment in the time domain (see Gentner, 1985, for a review of data that also supports this view). The fact that movement was seen to be relatively specific to the context in which it was performed suggests that planning and control processes are sensitive not only to the needs and objectives of the performer but also to the current environmental conditions. In the introduction, we spoke of constraints as those factors that limit the manner in which movement control occurs, and the present results suggest that the performer tailors movements based on a number of constraints. In this regard, we agree with Nelson (1983) when he suggested that detailed dynamic models relating displacement coordinates in physical timespace to the net torques acting along these coordinates (through inverse dynamics) will be inadequate for explaining or predicting movement unless they also include the performance constraints and objectives which affect the neural and neuromuscular inputs. In essence, there is a dynamic interaction between knowledge (e.g., a person's past experience and movement objectives) and the biological structure of the human system. Thus, we suggest as a research strategy the investigation, identification, and classification of several broad areas of constraint or context that will influence movement production (MacKenzie & Marteniuk, 1985). These include, among others, constraints due to anatomical structure, neurological structure, conditions of speed versus accuracy, experience of the performer, structure in communicated information, and the movement task itself.

The notion that movement is influenced by constraints is directly supportive of a task specific view of movement planning and control. Here, *task* is defined as the interaction of the performer with the environment under given movement goals. This view predicts that movement is optimized and specific to the unique requirements that arise from an individual motorically interacting with the environment. As such, general and abstract representations of movement do not exist. However, neither do a myriad of specific motor programs. As Arbib (1981, 1985) has argued, movement representation consists of units of knowledge of interactions with the world (schemas) each of which corresponds to some domain such as objects, interlimb coordination, or social interaction. Reed (1982, 1984), from the ecologically oriented perspective of action theory, also supports the view that movements are functionally specific and believes action units to be defined ecologically.

Another line of work supported by the present results is that of Abbs and his colleagues (Abbs et al., 1984; Cole & Abbs, 1986). They have found support for task specificity in movement planning and control and have postulated that their results can be explained if movement planning is in terms of sensory consequences. Here, motor planning is seen as involving intersensory integration resulting from past successful completions of motor tasks. Also integral to their idea of how control occurs is the notion of tightly integrated sensorimotor centres where feedback from an evolving movement is processed in comparison with the motor plan, and appropriate motor adjustments are made. This framework explains not only the elegant specificity of motor control, but also how rapid, feedback-based motor corrections can be made.

## REFERENCES

Abbs, J.H., Gracco, V.L., & Cole, K.J. (1984). Control of multimovement coordination: Sensorimotor mechanisms in speech motor programming. *Journal of Motor Behavior*, **16**, 195–231.

Abend, W., Bizzi, E., & Morasso, P. (1982). Human arm trajectory formation. *Brain*, **105**, 331–348.

Arbib, M.A. (1981). Perceptual structures and distributed motor control. In V.B. Brooks (Ed.), *Handbook of physiology: Vol. 2, Motor control, Part 2*. Bethesda, MD: American Physiological Society.

Arbib, M.A. (1985). Schemas for the temporal organization of behavior. *Human Neurobiology*, **4**, 63–72.

Atkeson, C.G., & Hollerbach, J.M. (1985). Kinematic features of unrestrained vertical arm movements. *Journal of Neuroscience*, **5**, 2318–2330.

Carlton, L.G. (1980). Movement control characteristics of aiming responses. *Ergonomics*, **11**, 1019–1032.

Cole, K.J., & Abbs, J.H. (1986). Coordination of three-joint digit movements for rapid, finger-thumb grasp. *Journal of Neurophysiology*, **55**, 1407–1423.

Crossman, E.R.F.W., & Goodeve, P.J. (1963, July). *Feedback control of hand-movement and Fitts' Law*. Paper presented at the meeting of the Experimental Psychology Society, Oxford. (*Quarterly Journal of Experimental Psychology*, 1983, **35A**, 251–278.)

Fitts, P.M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, **47**, 381–391.

Fitts, P.M., & Peterson, J.R. (1964). Information capacity of discrete motor responses. *Journal of Experimental Psychology*, **67**, 103–112.

Flash, T., & Hogan, N. (1985). The coordination of arm movements: An experimentally confirmed mathematical model. *Journal of Neuroscience*, **5**, 1688–1703.

Gentner, D.R. (1985). *Skilled motor performance at variable rates: A composite view of motor control* (CHIP Report 124). San Diego, CA: Cognitive Science Laboratory, University of California.

Hollerbach, J.M., & Flash, T. (1982). Dynamic interactions between limb segments during planar arm movement. *Biological Cybernetics*, **44**, 64–77.

Jeannerod, M. (1984). The timing of natural prehension movements. *Journal of Motor Behavior*, **16**, 235–254.

Keele, S.W. (1981). Behavioral analysis of movement. In V.B. Brooks (Ed.), *Handbook of Physiology: Volume 2, Motor Control, Part 2*. Bethesda, MD: American Physiological Society.

MacKenzie, C.L., & Marteniuk, R.G. (1985). Motor skill: Feedback, knowledge, and structural issues. *Canadian Journal of Psychology*, **39**, 313–337.

MacKenzie, C.L., Marteniuk, R.G., Dugas, C., Liske, D., & Eickmeier, B. (in press). Three dimensional movement trajectories in Fitts' task: Implications for control. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*.

Morasso, P. (1981). Spatial control of movements. *Experimental Brain Research*, **42**, 223–227.

Munhall, K.G., Ostry, D.J., & Parush, A. (1985). Characteristics of velocity profiles of speech movements. *Journal of Experimental Psychology: Human Perception & Performance*, **11**, 457–474.

Nelson, W.L. (1983). Physical principles for economies of skilled movements. *Biological Cybernetics*, **46**, 135–147.

Pezzack, J.C., Norman, R.W., & Winter, D.A. (1977). An assessment of derivative determining techniques used for motion analysis. *Journal of Biomechanics*, **10**, 377–382.

Poulton, E.C. (1974). *Tracking skill and manual control*. London: Academic Press.

Reed, E.S. (1982). An outline of a theory of action systems. *Journal of Motor Behavior*, **14**, 98–134.

Reed, E.S. (1984). From action Gestalts to direct action. In H.T.A. Whiting (Ed.), *Human motor actions: Bernstein reassessed*. Amsterdam: North Holland.

Schmidt, R.A. (1975). A schema theory of discrete motor skill learning. *Psychological Review*, **82**, 225–260.

Schmidt, R.A., Sherwood, D.E., Zelaznik, H.N., & Leikind, B.J. (1984). Speed-accuracy trade-offs in motor behavior: Theories of impulse variability. In U. Kleinbeck, H. Heuer, & K.H. Schmidt (Eds.), *The psychology of motor behavior*. Berlin: Springer-Verlag.

Soechting, J.F. (1984). Effect of target size on spatial and temporal characteristics of a pointing movement in man. *Experimental Brain Research*, **54**, 121–132.

Woodworth, R.S. (1899). The accuracy of voluntary movement. *Psychological Review Monograph Suppl*, **3**, #3.

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