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On Fitts's and Hooke's laws: Simple harmonic movement in upper-limb cyclical aiming

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Can discrete, single-shot movements and continuous, cyclical movements be reduced to a single concept? In the classical, computational approach to human motor behaviour, cyclical aimed movement has generally been considered to derive from discrete primitives through a concatenation mechanism. Much importance, accordingly, has been attached to discrete-movement paradigms and to techniques allowing the segmentation of continuous data. An alternative approach, suggested by the nonlinear dynamical systems theory, views discreteness as a limiting case of cyclicity. Although attempts have been made recently to account for discrete movements in dynamical terms, cyclical paradigms have been favoured.

The concatenation interpretation of cyclical aimed movement is criticized on the ground that it implies a complete waste of mechanical energy once in every half-cycle. Some kinematic data from a one-dimensional reciprocal (i.e., cyclical) aiming experiment are reported, suggesting that human subjects do save muscular efforts from one movement to the next in upper-limb cyclical aiming. The experiment demonstrated convergence on simple harmonic motion as aiming tolerance was increased, an outcome interpreted with reference to Hooke's law, in terms of the muscles' capability of storing potential, elastic energy across movement reversals.

Not only is the concatenation concept problematic for understanding cyclical aimed movements, but the very reality of discrete movements is questionable too. It is pointed out that discrete motor acts of real life are composed of complete cycles, rather than half-cycles.

Introduction

Discrete versus continuous aimed movements

Students of human motor behaviour seem to have to accommodate themselves to the existence of two varieties of goal-directed move-

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ments: There are discrete, single-shot movements (e.g., reaching a button to switch on the light), and cyclical movements (e.g., juggling). Sooner or later, one is faced with the problem that there is no self-evident way of reducing these two varieties of movements to a single category (Beek 1989; Schöner 1990).

Fitts (1954) originally established his famous speed–accuracy trade-off law with a cyclical paradigm, the so-called reciprocal tapping paradigm, in which the subject had to tap alternately on two targets with a hand-held stylus for a few tens of seconds. Fitts later felt he had to check if his empirical law was still valid with discrete movements, which turned out to be the case (Fitts and Peterson 1964). In retrospect, this verification may be judged important, for the discrete aimed-movement paradigm is actually that which most subsequent, computationally-oriented studies of human motor control have used (e.g., Keele 1968; Meyer et al. 1982; Plamondon 1991; Schmidt et al. 1979).

In contrast, the approach to human movement that has recently developed in psychology under the joint influences of Gibson's (1966 1979) ecological theory and of the nonlinear dynamical systems theory (Abraham and Shaw 1983; Nicolis and Prigogine 1977) has favoured the study of continuous, cyclical movements (e.g., Beek 1989; Kelso 1981; Kugler and Turvey 1987; Turvey et al. 1978), coming to terms more reluctantly with the discrete case (for attempts to adapt the conceptual tools of dynamics to discrete movements, see Saltzman and Kelso 1987, and Schöner 1990).

The everyday motor repertoire of humans comprises innumerable instances of cyclical *aimed* movements, besides the discrete instances. In handwriting, for example, one must concurrently handle the demands of speed and accuracy, which become contradictory beyond some point, as in discrete aiming. Other related examples are speech and typing, but outside the language sphere there are obviously numerous instances of everyday-life manual activities that are goal-directed while being cyclically organized (e.g., knitting, embroidering, making a knot, hammering, etc.). An interesting general issue, therefore, is whether knowledge relevant to discrete movement can be generalized to cyclical movements. Put differently, to what extent can discrete movement be considered a primitive?

In keeping with the computational tradition, one may conceive of cyclical movement in terms of a *concatenation* of discrete movements viewed as building blocks. To concatenate items (from the latin *catena*, chain) is to arrange them sequentially. For instance, a sentence is a concatenation of clauses, and a digital-computer programme is a concatenation of commands. Likewise, some authors have hypothesized that handwriting amounts to the concatenation of individual pen strokes (e.g., Morasso and Mussa Ivaldi 1982; Teulings et al. 1986). According to Morasso (1986: 156), cursive script is 'generated by a quasi-periodic mechanism which uses, as primitive elements, trajectory segments with spatio-temporal characteristics similar to targeted movements'. [1]

Such an understanding of the discrete/continuous relationship can be labeled bottom-up in contrast to that offered by the dynamical systems view. In this latter view, serial order emerges in the context of cyclicity from the very continuity of the movement. Whereas the computational approach seeks the origin of serial order in *rate-independent structures*, namely, decomposable motor plans, the dynamical systems approach offers an account in terms of *rate-dependent processes*, namely, those basic, undecomposable dynamical laws of nature whereby visible order emerges from fluxes of matter and energy (Carello et al. 1984). From the dynamical perspective, empirical knowledge gained with discrete paradigms seems of little help for the study of cyclical movement. Discrete movement cannot be held as a primitive. Contrary to the computational view that cyclicity derives from discreteness (which in some sense implies that the cyclical case is subsumed by the discrete case), the dynamical systems approach to human motor behaviour leads one to consider discrete movement a special, limiting case of cyclical movement, namely, the case in which the number of consecutive cycles is just 1/2.

The concatenation hypothesis and the segmentation of data

The possibility of a discrete-movement concatenation mechanism has been seldom discussed in the literature on motor behaviour. One

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[1] Notice that in this quote 'targeted' movement is implicitly likened to discrete movement. It should be noted, however, that the property of targetedness for limb movements is certainly not the hallmark of discreteness, many cyclical movements of real life being target-directed too, as remarked above.

will usually fail to find 'concatenation' as an entry in a subject index, as though the concatenation concept were irrelevant, or evidently true. In fact, there are reasons both to suspect that the discrete-movement concatenation assumption works as a more or less tacit postulate in the computational approach, and to question the validity of this assumption.

One reason for suspecting more or less tacit adherence of computational psychology to the discrete-movement concatenation hypothesis is that, as already mentioned, research on motor control has focused on discrete-movement paradigms. If the computational approach purports to provide a general account of motor behaviour, then from a strategic point of view emphasis on discrete movement must be deemed unreasonable *unless* discrete concatenation is believed to provide a negotiable bridge from discreteness to cyclicity.

A further reason is that a great deal of effort has been made to design segmentation techniques for the analysis of human continuous movement such as handwriting or drawing. For example, great importance has been attached to the fact that a sustained curvilinear movement (e.g., drawing an ellipse repeatedly, or scribbling) can be decomposed into a succession of units of action each having its own kinematic characteristics (Viviani and Terzuolo 1982; Viviani 1986). The point being made is that the segmentation issue has limited relevance to the study of continuous, cyclical movement *unless* the continuity of the movement is assumed to derive from discrete primitives through a concatenation mechanism. In other words, recourse to discretizing techniques is likely to imply the assumption of underlying discreteness.

The kinematics of concatenation

The key property of concatenation is that it assembles *pre-existing* elements, the identity of which is independent of, and conserved through the assembling. Thus, the hypothesis that a cyclical activity like handwriting derives from the concatenation of discrete movements implies that the kinematic characteristics of the discrete 'primitives' be essentially unaffected by their being inserted into a continuous, multi-periodical movement. As will become apparent, however, this cannot be true in general.

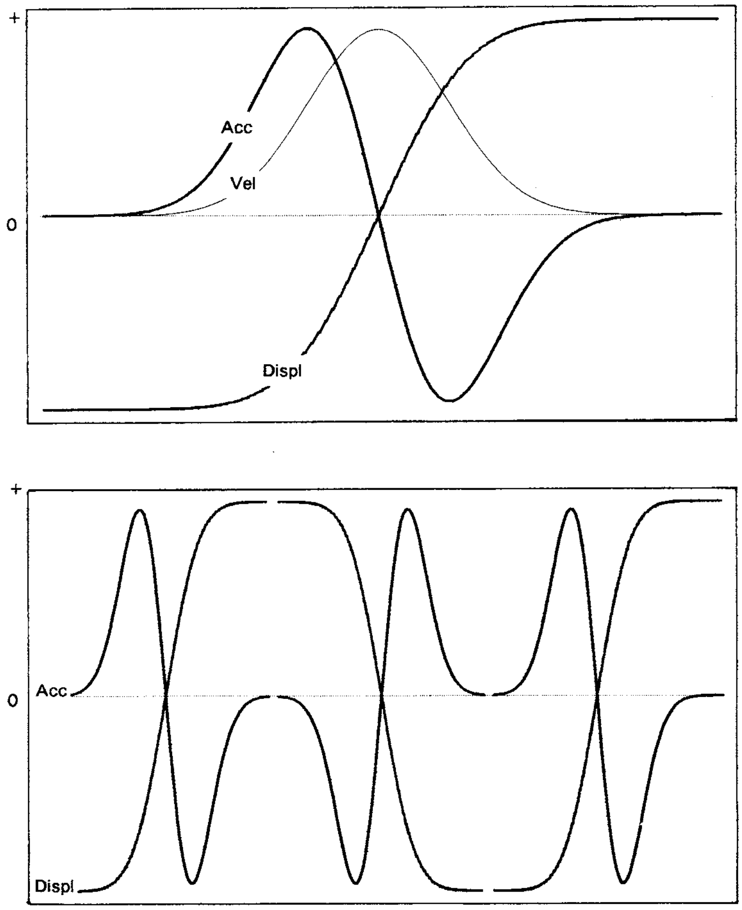

Fig. 1. The kinematics of discrete-movement concatenation. Upper panel: schematization of a discrete, point-to-point aimed movement, with its typical biphasic acceleration profile. Lower panel: illustration of the concatenation of three discrete primitives, showing two successive peaks of acceleration for each movement reversal.

Let us consider what the concatenation of discrete movements means precisely, with a hypothetical example in the simple case of one-dimensional movement. Fig. 1 (upper panel) depicts the displacement, velocity, and acceleration profiles of a discrete, point-to-point movement. The velocity profile is bell-shaped, [2] but we have two

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[2] In a typical discrete aimed movement the velocity profile is more or less asymmetric (Plamondon 1991). Here, however, an unskewed Gaussian curve was felt sufficient for the argument.

opposite phases in the acceleration profile, the first corresponding to the force responsible for the creation of the motion and the second to the force responsible for its cessation. Note that in a discrete movement all the kinetic energy created by the initial impulse is dissipated during the terminal braking phase, because, by definition, there is nothing to do following the completion of the movement.

Fig. 1 (lower panel) also illustrates the displacement and acceleration profiles we obtain if we concatenate three discrete movements like that described in the upper panel, but of alternate directions. By construction, the acceleration profile remains biphasic for each movement or half-cycle. For example, the second movement, oriented to the left, starts with a leftward force (negative acceleration in the figure). Note that the preceding movement, oriented to the right, has just ended with a leftward force, but this was for coming back to rest, and consequently all has to be done again. Thus, the concatenation of discrete primitives conserves intact the dissipative braking phase of each primitive movement. This is obviously problematic because in a sustained to-and-fro movement a single force event may do perfectly well to simultaneously terminate each movement and start the next.

Kinematics and kinetics: Fitts's and Hooke's laws

Fitts's law, taken in a broad sense, expresses about movement execution a general relationship between time and space. [3] It must be pointed out that because Fitts's law ignores mass, the third basic physical dimension, and by the same token the various physical quantities that involve a mass factor such as force and energy, it is confined to the *kinematic* domain.

Besides informational, kinematic constraints, however, there are *energy* constraints in aimed movements (Nelson 1983), and therefore

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[3] One can demonstrate essentially the same speed–accuracy tradeoff in an aiming task either by experimentally manipulating the spatial constraint (the ratio of movement amplitude to target size) and treating movement time as the dependent variable (as in Fitts's (1954) original paradigm), or equivalently by controlling movement time and amplitude as independent variables and treating the spatial variability of the aiming response as the dependent variable (Schmidt et al. 1979). The basic equivalence of the spatially-constrained paradigm and the temporally-constrained paradigm was first pointed out by Meyer et al. (1982).

some reference to kinetics may be pertinent to the issue under consideration. Fitts and Peterson (1964), as already mentioned, showed discrete and cyclical aimed movements to be governed by similar spatio-temporal constraints. In no account, however, does this demonstration imply the kinetic equivalency of the two sorts of movement. Considering movements in terms of energy economy, it should be realized that cyclicity offers the acting organism the valuable possibility, not available in the discrete case, of saving mechanical energy (i.e., effort) from half-cycle to half-cycle, thanks to the ability of muscles to store mechanical energy in a potential, elastic form towards the end of each movement to the benefit of the next. This is because muscles, which represent a chemical machinery capable of generating motion from rest by contracting actively, also constitute springy bodies capable of functioning *passively* as reversible converters of kinetic energy into potential energy, and of potential energy into kinetic energy (Cavagna 1977; Van Ingen Schenau 1989). To the extent that the muscular system recovers a debt, movement can be produced at no energy cost.

The fact that the energy spent in deforming a body, whether made up of living tissue or lifeless material, is not necessarily lost can be understood in the light of a principle of classical mechanics known as Hooke's law (see fig. 2). Matter can store, and therefore restore the work done on it. Considering ideally elastic bodies from the point of view of statics, Hooke stated the proportionality of restoring force, or stress, and relative deformation, or strain. Associated with Newton's laws of motion, Hooke's law sheds light on the behaviour of all sytems that have not only mass, capable of carrying kinetic energy, but also elasticity, capable of storing potential energy. In an ideal mass-spring system (i.e., one with a perfectly linear spring and no friction), motion will go on indefinitely from the moment it has started, because mechanical energy is entirely conserved through a continuous interchange of kinetic and potential energy. The system is said to be perfectly conservative.

Simple harmonic movement and economy of effort

Kinematically speaking, an ideal mass-spring system produces an oscillatory behaviour classically known as *simple harmonic motion*: Once released from a position away from the equilibrium point, the

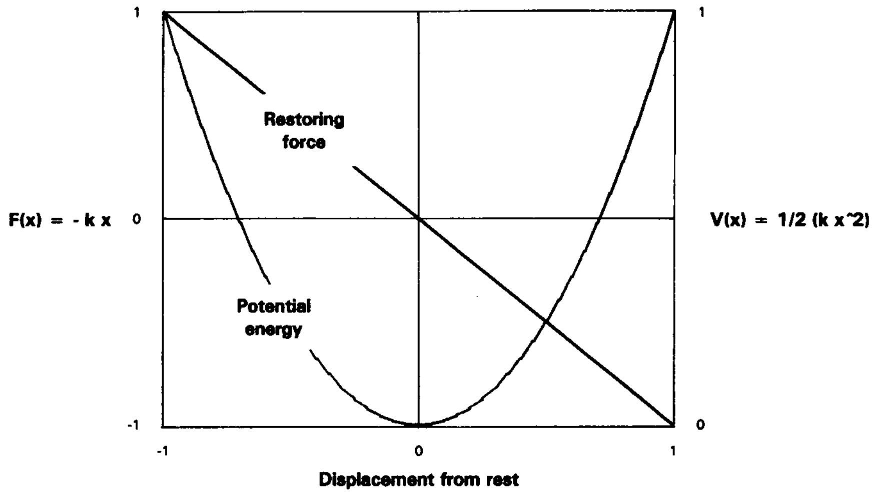

Fig. 2. Hooke's law. Restoring force $F(x)$ is proportional to the magnitude of the displacement x, and directed towards the equilibrium point at $x = 0$. The slope of the function expresses the stiffness of the elastic body. Also represented is the potential-energy function $V(x)$ for the free oscillation of an ideal mass-spring system, letting the oscillation vary from -1 to 1 and setting the (constant) total mechanical energy E to 1. At zero displacement, all the energy is kinetic with $V(x) = 0$. At each displacement extremum all the energy is under the potential, elastic form with $V(x) = E = 1$.

mass will start oscillating in a sinusoidal fashion, with no damping. Needless to say, both the frictionlessness and the linearity assumption make the model look rather irrealistic for the study of the behaviour of actual things and beings, but these problems can be handled, as suggested in the following.

Friction is ubiquitous in nature, and the motion of an actual mass-spring system will exhibit damping down to immobility, rather than a sustained oscillation. Yet, it is known since Huygens that this departure from the conservative ideal can be covered up by means of an *escapement* device (see Kugler and Turvey 1987). For example, the escapement of a mechanical clock offsets friction by periodically injecting a squirt of fresh energy into the system, thereby making sustained oscillation possible. Assisted by some escapement,[4] the

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[4] As shown by Kugler and Turvey (1987), the fixed phase-dependent escapements used in timepieces provide a poor analogy for sustained rhythmical motion in living organisms. These authors offer an alternative design for the modeling of biological escapements, in a dissipative-structure perspective.

mass-spring system thus becomes worthy of consideration for modeling the cyclical movements of living organisms. The model remains remarkably parsimonious, for the energy inflow into the system ensured by the escapement has just to offset the energy outflow due to friction.

As for the linearity assumption, it is known that with actual materials Hooke's static proportionality holds good in general only for very small deformations, that is to say, the force vs. deformation function generally has quite a limited linearity range (e.g., French 1971). It must be recalled, however, that a great variety of man-made elastic devices do abide by Hooke's linear law with little restriction. For example a coiled spring, whether made up of steel, wood, or glass, will obey Hooke's law over any arbitrarily large deformation range, provided that its *global* geometrical design is appropriate – even though locally the law remains an overgeneralisation, as would inevitably reveal a complete test of the local force vs. deformation function at some arbitrary point on the coil. The important fact is that at some macroscopic scale of analysis there exist systems that do behave as simple harmonic oscillators, in keeping with Hooke's law. Although sinusoids are sometimes felt to represent just convenient mathematical abstractions (e.g., Wann et al. 1988), it seems fair to recognize that simple harmonic motion actually belongs to the realm of physical reality.

In sum, the linear mass-spring system, assisted by an escapement, is an appealing candidate for modeling the sustained cyclical movement of a limb. Not only is the model parsimonious as a research tool – in the sense that it involves just three components – it also has the merit of sensibly assuming energy parsimony in the behaviour of acting organisms.

The complex skeletal morphology of a vertebrate seems to preclude any functional linearity. Yet, there is empirical evidence in humans that some rhythmical multiple degree of freedom movements are indeed amenable to the simple mass-spring model (see Kelso 1986). For example, with the so-called reiterant speech paradigm, Kelso et al. (1985) have demonstrated harmonicity in the kinematics of the lips and jaws.

Some further evidence from a task involving the upper limb will be reported below. Note that we are now considering the problem of harmonicity in the context of cyclical *aimed* movements.

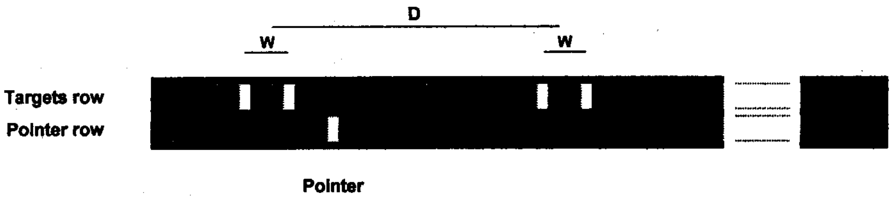

Fig. 3. A schematic representation of the visual display. The upper display, a row of 512 red LEDs, served to represent the two targets in the form of two pairs of fixed luminous dots (unfilled rectangles in the figure) of width W and separated by a distance D. The lower display, a row of 512 green LEDs, served to represent the mobile pointer (unfilled rectangle).

The experiment

In this experiment one-dimensional cyclical movements were recorded in an aiming task of variable difficulty. The alteration of the movement kinematics as a function of task difficulty was of particular interest, having in mind the discrete-movement concatenation hypothesis.

Methods

Four adult volunteers were used as subjects. Their task was to move a visual pointer from one target to another as quickly as possible, though with very few errors. They controlled the motion of the visual pointer by moving a manipulandum back and forth along a linear track, using their preferred arm.

The targets were two pairs of luminous dots presented immobile on a row of 512 red light-emitting diodes (LEDs). This visual display, oriented horizontally, was placed at eye level, facing the subject, with a viewing distance of about 120 cm. Throughout the experiment, between-target distance (D) was a constant 128 LEDs (about 13° visual angle), whereas target width (W) varied from condition to condition. The values of W were 16, 8, and 4 LEDs (about 1°36′, 48′, and 24′ visual angle, respectively). Thus, using Fitts's (1954) formula, the index of difficulty (ID) in the task was 4, 5, and 6, respectively.[5]

The pointer was represented to the subject by a single luminous dot on a second row of 512 green LEDs placed parallel to and just below the just-mentioned target row (see fig. 3). The instantaneous position of this luminous dot was refreshed by the computer at the frequency of 500 Hz, so that the pointer's motion along the left–right

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[5] We here refer, for convenience, to Fitts's (1954) historic formula:

$$\text{movement time} = C_1 + C_2 ID,$$

with C_1 and C_2 standing for adjustable constants and $ID = \log_2(2D/W)$. It must be mentioned that the literature offers a number of nonlogarithmic reformulations of Fitts's law that lead to improved data fits (e.g., Meyer et al. 1982; Plamondon 1991; Sheridan 1991).

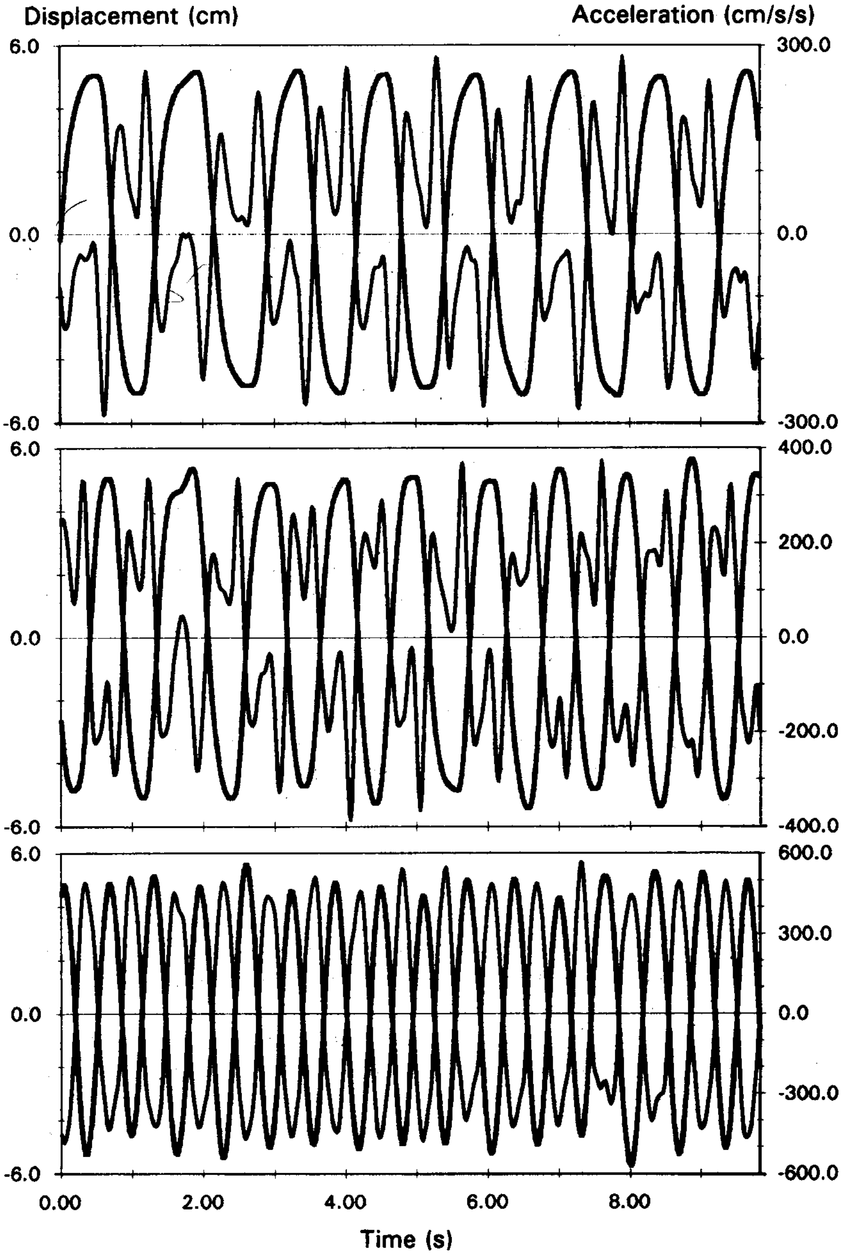

Fig. 4. Examples of displacement and acceleration time profiles for $W=4$ ($ID=6$), $W=8$ ($ID=5$), and $W=16$ ($ID=4$), from top to bottom. Displacement (thick tracings) is the distance from the oscillation midpoint. Acceleration (thin tracings) has been computed with an differentiation algorithm that induces no phase lag. Note the rescaling of the magnitude of acceleration, but not displacement.

continuum could be controlled with the manipulandum in an apparently continuous fashion. In one trial, the subject had to reach alternately the left- and right-target interval with the pointer as many times as possible for 30 s, while avoiding overshoots. The gain with which the manipulandum controlled the motion of the pointer was fixed, with a carriage translation of about 10 cm required for the pointer to cover the 128-LED distance from one target-center to the other.

The manipulandum was a wheeled carriage with very little friction and a total course of 31 cm. The orientation of the track was 30° relative to the horizontal. A virtually frictionless rectilinear potentiometre (Schlumberger CD 4321/6) was fixed to the manipulandum. During the experiment the movements were sampled by the computer at a frequency of 500 Hz, but for the off-line processing of interest in the present report a 20-ms sampling period (50 Hz) was judged sufficient. Only the last third of each trial was considered (the final 10 s of the trial). To reduce noise, the position time series were smoothed with a mobile three-point average. This simple procedure was repeated on velocity data before proceeding to the second differentiation.

In this report, we shall leave velocity aside, to focus on position and acceleration of the manipulandum. These two dependent measures will be presented together, in turn as time profiles (see fig. 4) and in the form of acceleration/position xy plots (see fig. 7). One reason for taking position, or displacement, into consideration is that an aiming task is defined operationally in terms of position – that is to say, for both the subject and the experimenter it is a positional criterion that distinguishes a correct movement from an error. On the other hand, acceleration is of privileged importance because it represents a window into the kinetic domain. If, in a given situation, the inertia resisting the motion is constant, then, by Newton's second law, changes in the acceleration of the mass kinematically specify changes in the net force exerted on the mass (see Runeson and Frykholm's (1983) concept of KSD (kinematic specification of dynamics) in the context of visual perception).

Results and discussion

Fig. 4 illustrates the way in which the time profiles of position and acceleration over the 10-s recording were affected by changes in task difficulty, in one representative subject that had practised for about an hour in each condition. The three examples shown are typical recordings under conditions of increasing movement tolerance, with $W = 4$, $W = 8$, and $W = 16$ from top to bottom (Fitts's $ID = 6$, 5, and 4, respectively).

The frequency of the oscillation increased markedly as movement tolerance increased, as of course must be expected from Fitts's law – one period in the cyclical aiming paradigm representing the sum of two consecutive movement times. The form of the three displacement curves, however, do not differ appreciably, all of them looking more or less sinusoidal.

The picture is quite different, however, when acceleration is considered. As illustrated in the upper panel of fig. 4, in the high-difficulty condition ($ID = 6$) each individual movement had a clearly biphasic acceleration profile. Between two consecutive peaks with the same sign, the acceleration tended to cancel out at about the instant that the movement reversed.

If the outcome, so far, seems consistent with the concatenation hypothesis of fig. 1, the data from less difficult conditions, shown in the middle and lower panels of fig. 4, make matters worse for this hypothesis. When the tolerance was first raised from $W = 4$ to $W = 8$ ($ID = 5$, middle panel), a considerable reduction occurred in the depth of the separating wells. With a further increase of tolerance to $W = 16$ ($ID = 4$, lower panel), the wells disappeared altogether, the two peaks of acceleration merging into a single event. Now the overall acceleration profile has the form of a sinewave – which implies that the displacement curve from which acceleration has been computed is indeed a sinewave.

The extent to which, at movement reversals, terminal braking and initial re-acceleration fuse is of particular interest because, as already pointed out, such a fusion reflects the saving of mechanical energy. To characterize this saving quantitatively in the data in terms of an index of harmonicity (H), the following analysis was carried out (see fig. 5 for an illustration of the method). In the first place, all the local extrema (LEs), that is, all minima and maxima, were identified in the acceleration time series (LEs of acceleration are marked with squares in fig. 5). In the second place, all the zero crossings of displacement – measured relative to the oscillation spatial midpoint – were detected over the time series, so as to segment the recording into a succession of nonoverlapping time windows, each of which comprised a single movement reversal (three such time windows, labeled A, B, and C, are represented in fig. 5). Third, the value of H was computed for each individual time window, using the set of LEs of acceleration identified within the time window considered: for time windows with positive displacement (negative acceleration), H was computed as the ratio of maximal LE to minimal LE; for time windows with negative displacement (positive acceleration), H was computed as the ratio of minimal LE to maximal LE. If

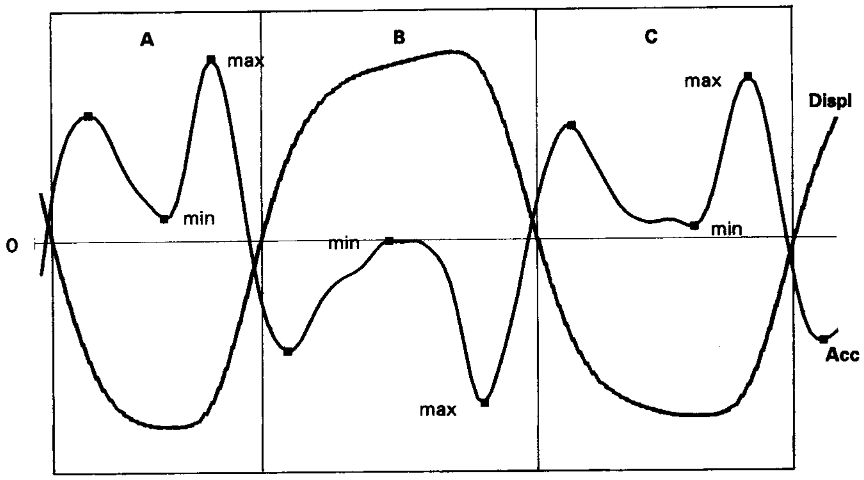

Fig. 5. Illustration, with a highly inharmonic example, of the procedure used to determine H, the index of harmonicity for a given movement recording (explanations in the text).

an acceleration LE had been detected that directed the pointer *away* from the oscillation midway, yielding a negative H, H was set to 0 (a negative value of H, obtainable whenever, to correct an excess of braking, re-acceleration takes place, would unsatisfactorily reflect a more than total dissipation of mechanical energy). Finally, the set of individual values of H were averaged over the whole recording to yield a global estimate of H.

By construction, the index of harmonicity H varies from 0 to 1. If the well is so deep that acceleration cancels out (i.e., the subject comes to a full stop upon movement reversal) or even changes its sign, we obtain $H = 0$, a measure specifying complete inharmonicity, that is, pure concatenation of discrete movements. At the other end of the harmonicity range, if the acceleration profile is sinusoidal, only one LE is detected in the time window: In such a case, H equals the ratio of this LE to itself, hence $H = 1$, specifying complete harmonicity. [6]

In the data collected in this experiment, the mean harmonicity index never quite reached 0 in a trial, even at $ID = 6$. In other words, movements could never be completely inharmonic in this cyclical aiming task. To examine the effect of Fitts's ID on H, one of the four subjects was asked to participate in a supplementary session in which a wider range of variation was explored for W. The results of this complementary investigation are illustrated in fig. 6.

The manipulation of movement tolerance dramatically affected the degree of harmonicity of cyclical movements. The decrement of H with increasing ID was strongly nonlinear, following an exponential decay law ($r^2 = 0.978$). Note that the intersection of the exponential curve with the horizontal line at $H = 1$ determines a critical value of ID. It is below this threshold of ID that the movement can be deemed completely harmonic. This particular set of data suggests that the movement became harmonic at about $ID = 3.2$, a value well within the [2,8] range over which most studies have examined Fitts's law. Thus, not only is it apparent that the measure of harmonicity, a quantity affected by tolerance in a systematic fashion, is relevant to the domain of cyclical *aiming*, but it is also clear (perhaps contrary to one's intuition) that the property of *full* harmonicity is not specific to spatially unconstrained cyclical movements.

Fig. 7 was prepared with the same data as fig. 4, but now acceleration is plotted against displacement, with no more reference to time. The reason for this new plot, which we may call a Hooke portrait, is that it depicts expressively the extent to which a sample of oscillatory movement follows Hooke's law (see Kelso 1986). In this representation, simple harmonic motion is specified by a linear graph, whose slope denotes the stiffness of the elastic components involved.

The figure illustrates how the increase in movement tolerance changed the shape of the trajectory formed by the data points in the acceleration-position plane (again, from top to bottom, $W = 4$, $W = 8$, and $W = 16$). In the upper plot, we obtain a highly nonlinear graph, exemplifying a case of 'soft' nonlinearity (Jordan and Smith 1977). There are four equilibrium points (Feldman 1986), two near the midpoint of the

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[6] For assessing the degree of harmonicity of oscillatory movements, the above method has the advantages of (i) measuring harmonicity separately for each individual half-cycle, and (ii) being applicable regardless of variations of the fundamental frequency.

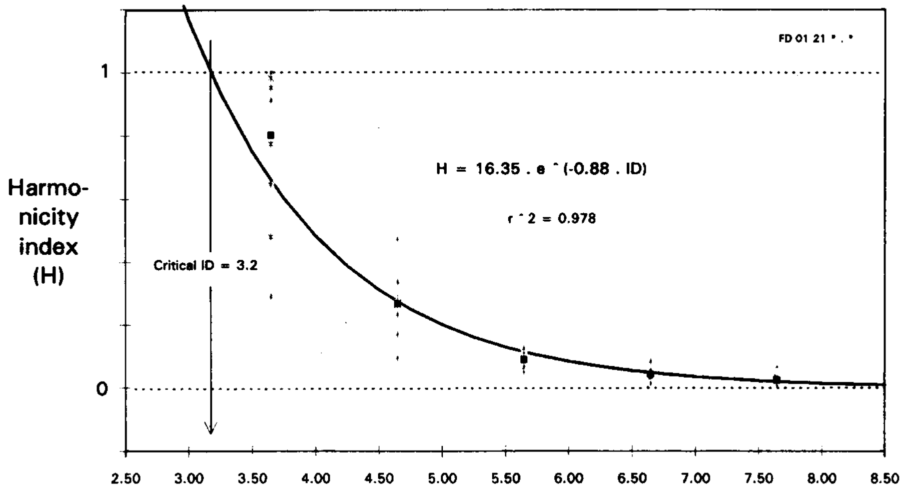

Fig. 6. Variation of the index of harmonicity H as a function of Fitts's ID. Crosses correspond to individual recordings. At each level of difficulty, the full square represents H averaged over 8 recordings.

oscillation (but not at it), and another two at the displacement extrema. For small displacements, the acceleration of the manipulandum – taken in this analysis as the measure of the net force exerted on it by the upper limb – is opposite to the displacement from equilibrium; it is apparent, however, that the acceleration is less than proportional to the displacement. For extreme excursions on either side (at the points where target homing-in takes place), the acceleration eventually drops to zero. This means that the mechanical energy has been dissipated altogether.

The Hooke portraits presented in the middle and lower panels of fig. 7 show that reducing the spatial constraint in the cyclical aiming task made the acceleration-displacement function converge on linearity. As the tolerance was raised from $W = 4$ to $W = 8$, the soft nonlinearity was appreciably reduced, with most movements reaching the equilibrium point (zero-acceleration) only once, at a position close to the midpoint. With the tolerance further increased to $W = 16$ (Fitts's $ID = 4$) an almost perfect linear graph was obtained. Thus, taking acceleration as a measure of force, we may say that provided that the cyclical task under study was easy enough – while indeed remaining an aiming task – the subjects behaved in accordance to Hooke's law.

Conclusions

The hypothesis that in goal-directed upper-limb movements cyclicity arises from the concatenation of discrete primitives seems hard to

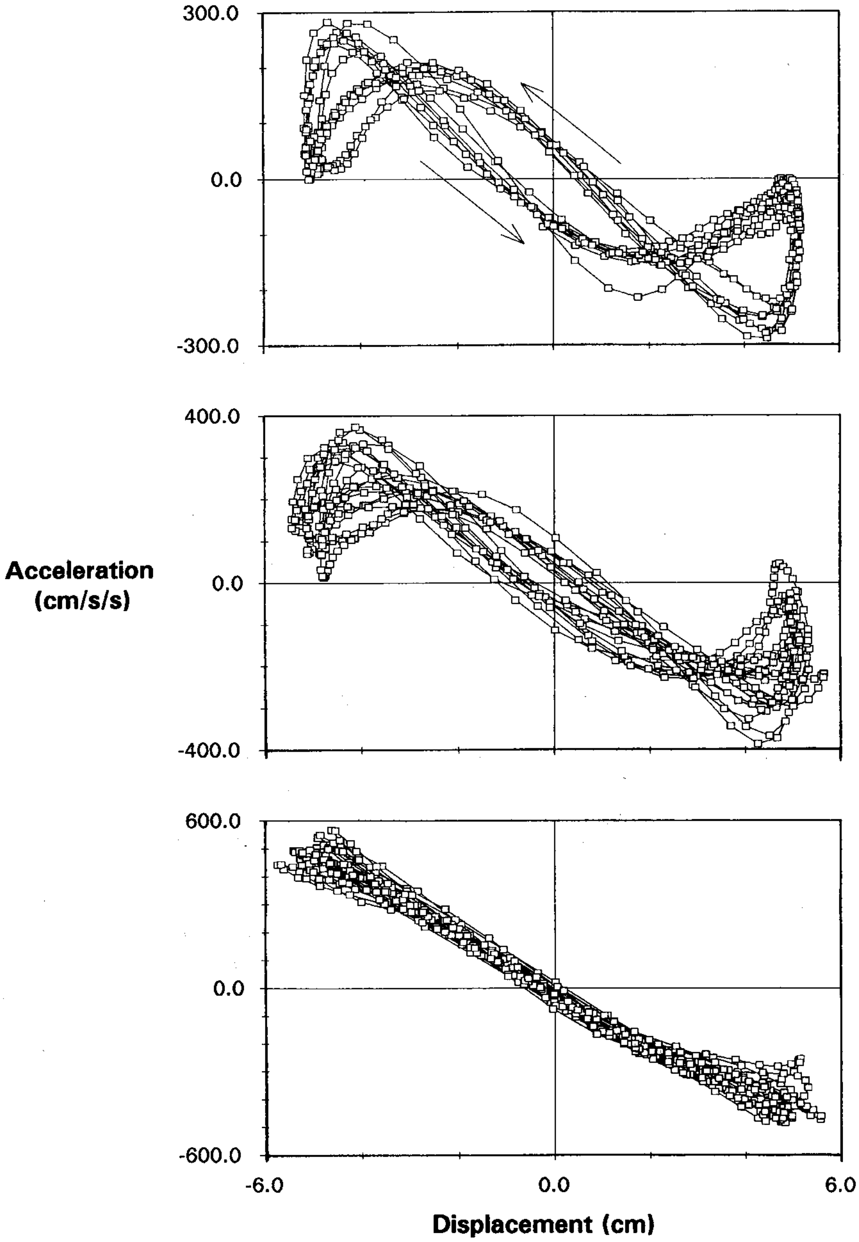

Fig. 7. Hooke portraits of the oscillatory movement. From top to bottom, $W = 4$ ($ID = 6$), $W = 8$ ($ID = 5$), and $W = 16$ ($ID = 4$). Note that the data are the same as in fig. 4. See explanations in text.

reconcile with the findings of this experiment. The subjects tended to treat each movement reversal, linking the initiation of one movement to the cessation of the preceding, as a single motor event, and exhibited convergence towards simple harmonic movement, the oscillatory regime that maximizes the saving of mechanical energy across cycles. Thus, the results point to the suggestion that for upper-limb movements the validity of the discrete-movement concatenation hypothesis is limited to slow cyclical movements performed under rather stringent spatial constraints.

Harmonicity and co-articulation effects in language-expression activities

It seems relevant to establish a parallel between the present observations and the so-called coarticulation effects found in a variety of language-expression activities such as speech and handwriting (see Thomassen and Schomaker, 1986, for a brief review). In these domains, the best-tried models are ones postulating the existence of discrete units of action to be assembled by concatenation – phonemes and pen strokes (or graphemes). Yet, coarticulation effects have been repeatedly observed, that is, the hypothetical units of motor action are so elusive that the view that language production is discrete seems to be squarely falsified by the behavioural evidence. Whereas they are troublesome for any discrete theory, co-articulation effects are readily interpretable in terms of economy of effort.

A problem, however, is that there seems to be no alternative to the classical theory that language, be it produced vocally or by some other means, is organized according to a combinatorial hierarchy of *distinctive* elements (de Saussure 1916). One must apparently recognize both the continuous character of skilled linguistic *performance* and the discreteness of linguistic *competency* (Chomsky 1975). Thus, simulation and modeling seem forced to cope with the so far unsolvable contradiction that activities of linguistic expression are continuous, energy-constrained processes whose *raison d'être* is to convey discrete symbols (see Meulenbroek and Thomassen, this volume).

Questioning the discrete-movement concept

If the validity of the concatenation hypothesis is problematic, how about the building blocks, the hypothetical discrete primitives? Interestingly enough, the very reality of discrete movements seems just as questionable as the reality of the concatenation mechanism. As argued below, single, but complete cycles represent more plausible units of motor action than isolated half-cycles.

Instances of so-called discrete movements of common interest in laboratory research are movements of pointing, grasping, and hitting. These upper-limb movements are characterized as discrete because they are assumed to start at some point and end at another point. This of course is operationally correct. Following the completion of each movement, however, the limb will inevitably have to return to the starting position for a new trial. Thus, in a discrete paradigm each individual act is in fact a to-and-fro, cyclical movement, only the first part of which is experimentally controlled and analyzed.

Repetitive reference, in the computationally-oriented literature, to the discrete-movement paradigm has the effect of inducing one particular view of motor action, one that is familiar, but no less questionable. It can be argued that the very concept of discrete movement is faulty in that half-cycles fail to capture the essence of real-life gestures like pointing, grasping, and hitting.

The claim that cycles, rather than discrete movements, constitute the ultimate, irreducible units of motor action at the scale of overall behaviour can be justified in the first place on geometrical grounds. In the vertebrate species considered in priority by movement psychologists, body parts are linked by joints that have a finite angular range. As a consequence, limbs can produce neither truly discrete, nor truly continuous movements. Unlike certain bacteria known to be equipped with a continuous rotary locomotor organ (Adler 1987), macroscopic animals are constrained by the fact that following flexion at some joint the only event that can occur is an extension and vice versa. In other words, cyclicity is the only geometrical possibility over time.

A further argument for taking full cycles as the units of human and animal action is supplied by the results of this experiment. Whereas, as emphasized, a half-cycle is totally dissipative, a single, yet complete cycle can be more or less conservative because mechanical energy can be stored at the reversal. Therefore, discrete acts of real life are unlikely to resemble the discrete movements of experimental subjects, which break cycles into pieces.

The greater the momentum involved, the greater the energy waste caused by the decomposition of a cycle into two discrete movements.

It follows that amongst the movements traditionally considered discrete in psychology, those involving a high velocity and/or a high inertia are particularly likely to exhibit a one-cycle organization. In fact, there is little doubt that in sports, throwing and hitting gestures typically obey this principle. Sportsmen know by experience that the saving of mechanical energy makes it possible to improve performance at a constant cost, or to reduce the cost at a constant level of performance, or even to improve performance while simultaneously reducing the cost. There seem to be no reasons to hold the sports instance as special.

Finally, the suggestion conveyed by the dynamical systems literature that living organisms in general behave cyclically seems quite sensible. It remains that within the context of cyclicity the problem of spatial goal-directedness has perhaps received too little attention. The spatially-unconstrained rhythmical paradigms popular in the dynamical systems approach seem suitable indeed to the understanding of lower-limb movements for locomotion (see Kugler and Turvey's, 1987, rationalization of their wrist-pendulum paradigm). These paradigms, however, have been so far of limited value for the study of visually-directed movements of the upper limb in humans. Consideration of the aiming problem might represent one interesting direction for their future development.

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