

Task Coordination in Human Prehension

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ABSTRACT. Movement patterns may be complex in the sense of being composed of separable component tasks. These components may be coordinated at some level by the voluntary motor system, in order to combine tasks into appropriate actions. This study describes the use of task interference methods and phase transition curves (PTCs) to quantify task interference in tasks that may have two components. Comparison of the effects of task interference on the different components suggests how these may be coordinated during normal movements. These techniques can be applied to the coordination of hand transport and grasp aperture components in the reaching and grasping movements that people make in order to pick things up. Five subjects made cyclical movements that involved either composite reaching or just the transport or grasp component in isolation, according to condition. The cyclical movements were "perturbed" by requiring a rapid transport or grasping response to an auditory signal by the contralateral hand. The pattern of phase shifts, or changes in the timing of the cyclical task introduced by these perturbations was modeled using phase transition curves, in order to assess the nature of the functional linkage between transport and aperture in normal prehensile movement. The results suggest a functional linkage between grasp aperture and hand transport in normal prehensile movement.

Key words: grasping, human movement, phase transitions, task interference

There has been comparatively little interest, in the movement control literature, in complex movements that not only require coordination of multiple effectors but also involve two or more component tasks. Yet many human actions seem to involve separable elements that are themselves tasks. Consider manual tracking, for example: Skilled performance of this task requires both moving the eyes in pursuit of the target and also moving the manipandum along the trajectory of the target. These operations use different effector systems, and are additionally distinct in that each is a task with its own immediate goals. There may also be some degree of "communication" or information-sharing between component tasks, however, in order to facilitate their fusion into a single action. This information-sharing, or functional linkage, is an important characteristic of coordinated movement.

In producing multitask movements, the motor system may "parse" the overall goal into component tasks. In contrast with linguistic parsing (which decomposes a sentence into the smaller sections that together make up its meaning, and is hence purely analytic), motor task parsing is likely to be both analytic (complex movements must be decomposed into their components) and synthetic (the control of component tasks must be directed by the goals for the complex movement as a whole).

Methods for Studying Multitask Movements

A number of methods for identifying functional linkages of this kind have been proposed for multieffector movements. These include finding invariant relationships between effectors' trajectories (Soechting & Lacquaniti, 1981), finding common temporal patterns between neural activations of different effectors (Sears & Stagg, 1976), or finding stable movement patterns despite varying conditions of movement (Kelso, Saltzman & Tuller, 1986; Kugler & Turvey, 1988).

This paper combines four distinct elements to create an analogous method for identifying functional linkages at the task level, as opposed to the effector level. First, a modified task interference or dual-task paradigm is used to selectively disrupt the component tasks that contribute to a complex movement. Second, the primary task may be disrupted throughout its time course by applying a discrete, secondary task at various times. Third, the response of the primary

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task to interference is expressed as a function of the primary task phase using phase transition curves (PTCs). Finally, the secondary task is considered to have a constant effect on the motor control system.

Task Interference

Interference between two tasks has been held to reflect competition either for the capacity of a single, general-purpose central processing channel (Broadbent, 1958; 1982) or for specific cognitive resources or "modules" (Shallice, 1985).

The logic of task interference studies requires extension to tackle the issue of multitask movements. If a complex multitask movement consists of two component tasks, then it should be possible to find secondary tasks that perturb each component. Where the component tasks are encapsulated and do not communicate, it should be possible to disrupt each component task selectively without affecting the others. On the other hand, if component tasks share information, an interfering task aimed at disrupting one component task should also disrupt other components with which the first communicates. Thus, observing the behavior of the system as a whole in response to selective perturbations can reveal the communication between component tasks. This method will be called *complex task interference* (CTI).

When investigating the way in which the components of the primary task are combined in a normal complex movement, comparison of CTI and traditional, simple task interference (STI) results can be particularly valuable. Consider again the example of manual tracking. Suppose a secondary task, T, interferes with pursuit eye movements when these are performed in isolation (i.e., an STI condition) but does not interfere with moving the manipulandum through a trajectory. Now suppose T is performed during the course of a normal composite tracking movement (i.e., a CTI condition). Under these conditions, T may still interfere with eye movements and may now also interfere with the kinematic trajectory of the hand, perhaps because this trajectory is planned on the basis of oculomotor information. Alternatively, if less intuitively, the interference between T and oculomotor pursuit observed in isolation may now diminish or disappear, perhaps because the simultaneous occurrence of the kinematic trajectory of the hand alters the way in which oculomotor pursuit is executed, leaving the trajectory of the hand unaffected. Thus, comparing the effects of various interfering tasks on two or more components of a complex task can be used to study normal coordination of those components.

The Time Course of the Primary Task

Previous dual-task studies have generally used continuous tasks in both primary and secondary roles (see Welford, 1968, Table 4.2). But an alternative technique that measured the effect on a continuous primary task from a discrete secondary task would permit precise assessment of the control and processing required by the primary task

throughout its time course. Interference from discrete secondary tasks has previously been used in this way in probe reaction time studies (Posner & Boies, 1971; Posner & Keele, 1968). Posner and Boies visually presented a warning signal, followed by a letter and, finally, a second letter. In the basic experiment, both the warning interval and the interstimulus interval, which separated the appearance of the letters, were held constant. As the primary task, subjects were asked to judge whether the two letters were the same or different. The secondary task was a discrete response to a white noise probe, which could have occurred at one of several points in the sequence of primary task events. Posner and Boies found a systematic effect on the probe RT as a function of the point in the primary task sequence at which the probe occurred. Higher probe RTs were taken to reflect increased processing demands of the primary task, thus providing a history of the primary task's processing requirement.

Charting the time course of processing demands is a valuable adjunct to a task interference paradigm, because "time-sharing" may occur in many dual-task situations. A continuous record of processing demands can indicate epochs where time-sharing is a more or less attractive strategy. In the case of movements, it may also be particularly valuable to compare the temporal pattern of processing with the kinematic pattern of the observed behavior.

Phase Transition Curves (PTCs)

Continuous records of processing demands can also be achieved by considering the effects of a discrete secondary task on the primary task using phase transition curves (PTCs).¹ PTCs describe the effects of a single perturbation on a stable rhythmic behavior, using the observation that discrete perturbations can cause phase shifts (temporal advances or delays) in a cyclic behavior. PTCs represent the effects of the perturbation by an array of signed phase shift values considered as a function of the phase in the cycle at which the perturbation occurs. The magnitude of the perturbing stimulus generally alters the pattern of phase shifts, so many studies include stimulus magnitude as a parameter of the design. The effects on the cyclic behavior as stimulus phase and stimulus magnitude are varied permit an assessment of the stability, and thus the control, of the behavior.

The use of PTCs to analyze task interference involves modeling the system's response to perturbation in terms of its timing characteristics. Whereas PTCs are a relatively new method in psychology, phase shifts have often been noticed and discussed in the literature on human performance (e.g., the psychological refractory period, Kantowitz, 1974; Allport et al.'s "timing errors," 1972; Michon, 1966). Thus, the application of PTC methods seems promising.

To obtain the PTC, the phase of the cyclic behavior at a given instant is defined as the time since a particular reference event occurred, expressed as the modulus of the mean period of the cyclic behavior. Phase is normally measured from 0 to 1, with Phases 0 and 1 being equivalent. Using the example of manual tracking again, one could ask sub-

jects to track a cycling target, defining the point when the target passed a specified line on the screen traveling in a particular direction, say, as Phase 0.

Perturbations are delivered at a variety of phases in the movement's cycle (see Figure 1). The phase of the behavior at the end of the perturbation is termed the "oldphase" (Kawato, 1981). The phase shift is the temporal discrepancy between the phase of the observed postperturbation waveform and the phase of a hypothetical postperturbation waveform obtained by continuing the mean preperturbation waveform to infinity (the dashed line in Figure 1). Positive phase shifts conventionally indicate a phase delay (the observed waveform lags behind the hypothetical waveform), and negative phase shifts indicate a phase advance (the observed waveform precedes the hypothetical waveform). The phase shift observed on the i^{th} cycle after perturbation is termed the i^{th} transient phase shift. The oldphase $[\phi]$ plus

the i^{th} transient phase shift $[\Delta\phi_i(\phi)]$ equals the i^{th} transient newphase $[\phi'_i(\phi)]$, as follows:

$$\phi'_i(\phi) = \phi + \Delta\phi_i(\phi),$$

where $(i = 1 \dots n)$.

If the effect of the perturbation is sampled at a suitable range of oldphases, the phase transition curve itself can be plotted in a plane whose axes are the oldphase and newphase, either by connecting all observed sets of coordinates of oldphase and i^{th} transient newphase, or by fitting a regression line to these coordinates (Figure 4 will offer an example of this). The resulting curve is called the i^{th} transient PTC. PTCs differ from other performance measures in some important ways. First, each trial or observation contributes a single value for oldphase and as many transient newphase values as may be measured. Thus, successive transient PTCs are not independent. Second, the representation of phases is "biperiodic," that is, both abscissa and ordinate of the oldphase by newphase plane wrap around and repeat themselves continuously, because Phase 0 and Phase 1 are identical. Any data points that appear initially to be outliers may therefore be translated by adding or subtracting 1 to the oldphase or newphase coordinate, thus incorporating them into the rest of the distribution.

Some perturbations may cause a temporary phase shift of the motion in comparison with its normal, unperturbed pattern. These responses to perturbation are captured by the transient PTCs. When the system has recovered from perturbation and returned to its original cycle period, the phase of the perturbed motion may also return to normal, indicating the system's complete recovery from perturbation, or the phase shift caused by the perturbation may persist indefinitely. The "steady-state PTC" represents such long-term effects of the perturbation on the behavior. The experimental section of this paper, however, reports transient rather than steady-state PTCs, because adjustments to perturbed movements are likely to have low latencies.

Once obtained, the PTC's shape and topology can elucidate the stability of the behavior and suggest the nature of its control. If the perturbation has no effect, the result is a phase shift of zero: As the oldphase varies from 0 to 1, it is matched by the newphase, to yield a PTC with gradient 1 and intercept 0. At the other extreme, if the perturbation is so disruptive that the cycle is stopped entirely, then the PTC will have a mean gradient of zero, and some newphase values will not be represented at all, because the cycle will begin again at a constant phase, returning to square one, as it were. This may be described as a total "reset" of the behavior. Other, intermediate degrees of resetting are possible, as when the perturbation causes the cycle to restart within a restricted range of newphase values that are nevertheless a systematic function of the oldphase, resulting in a PTC with a mean gradient of zero, but with locally nonzero gradients. Comparisons of actual PTCs with these two benchmark patterns can be used to quantify the effects of the perturbation delivered. In general, PTCs for small per-

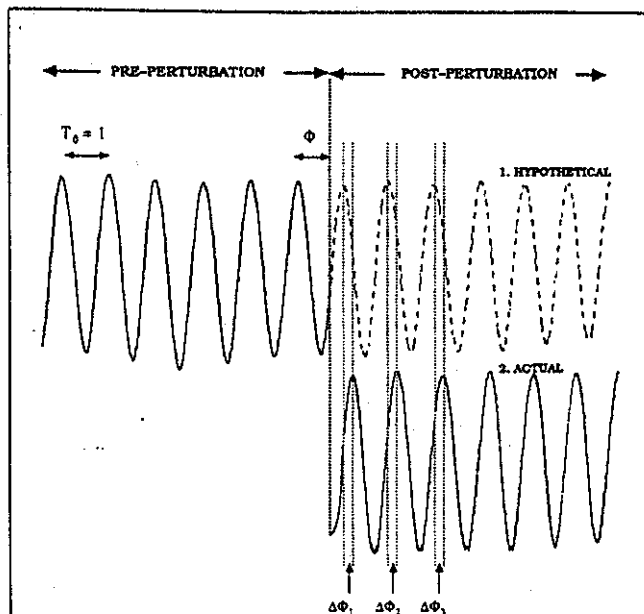


FIGURE 1. Definition of the phase transition curve (PTC). First, a reference event during the cycle is chosen, in this figure the peak of the waveform. All phase measurements are measured as moduli of the mean period of the preperturbation waveform; that is, the mean preperturbation period, T_0 , is assumed to be 1. The oldphase of the cycle is the phase of the cycle at which the perturbation ended. The first transient phase shift is the temporal discrepancy between the actual postperturbation waveform (solid line) and the preperturbation waveform hypothetically continued beyond the perturbation (dashed line) at the first reference event following the perturbation. As many transients as required may be measured. Larger (more disruptive) perturbations cause greater phase shifts. The first transient newphase is the oldphase plus the first transient phase shift. The first transient PTC is a fit to many data points representing the first transient newphase values plotted against the oldphase values. Perturbations may cause a simple linear delay or advance in the cyclic behavior or they may produce nonlinear phase shifts whose magnitude and sign depend on the oldphase.

turbations have mean gradients close to one, and those for larger perturbations have mean gradients close to zero. All PTCs observed in biological systems have belonged to one of these two basic geometrical categories (Winfree, 1988).

PTCs thus provide a diachronic measure of stability, suitable for probing control throughout a continuous primary task. But there are also the following caveats: First, the less stable the studied rhythm is in the absence of perturbations, the less reliable PTC methods will be. Second, large numbers of observations are required to assess the effects of perturbations delivered throughout the cycle. Finally, the extensive development of the PTC technique by mathematical biologists has not yet produced a set of accepted statistical procedures either for fitting appropriate curves to sets of datapoints, or for testing hypotheses about the effects of perturbations using PTC results—this topic will be discussed later.

Applying PTCs to Task Interference

The early use of PTCs in investigating biological oscillators, and their present use in task interference differ importantly as regards the nature of the perturbing stimulus. The former tradition employs known, quantifiable stimuli, as when examining the effects of a flash of light on invertebrate circadian rhythms (Pittendrigh & Bruce, 1957), and precisely manipulates the stimulus strength to investigate what patterns of phase resetting of the underlying oscillator can be induced. In the case of task interference, however, the “strength” of the perturbatory task is not directly quantifiable and, in fact, its measurement is the question being addressed by the investigation rather than a planned parameter of the experimental design. Thus, task interference studies must infer the strength of the perturbation post hoc from the PTCs themselves, using a suitable statistical procedure.

One such procedure is as follows. First, a constrained linear fit of newphase values on oldphase values is performed. The slope of the regression line is constrained to be 1, and the intercept constrained to be 0. This regression line corresponds to the PTC that would be obtained with no perturbation. A second, less constrained fit is then performed to obtain a PTC, which allows for any effect of the perturbation either by varying the slope or the intercept or by adding varying nonlinear terms to the regression function, so that the newphase values may be more accurately predicted from the oldphase values.

An incremental F statistic (Kerlinger & Pedhazur, 1973) then can be used to test for a significant difference in the quality of the fits, adjusting for any differences in the number of terms used in the two regressions. A significant and positive incremental F means that the additional varying terms in the second regression have captured an effect of the perturbation on the timing of the behavior. Significant and negative incremental F s are also possible because any additional terms may not improve the fit, while still using up degrees of freedom in the numerator. In this latter case, comparison of the two regressions would suggest that the

perturbation had no effect. The same conclusion follows when the incremental F statistic is not significant. Use of the incremental F can be extended to compare the quality of fit between any two stages in the regression procedure: Adding extra terms that genuinely capture the effects of the perturbation will produce a significant incremental F . The choice of which and how many terms are added to the regression to attempt to capture the effects of the perturbation is clearly of critical importance, and will be discussed later.

One comparison between regression fits is of particular theoretical interest. Comparing a linear fit to a second fit having both linear and nonlinear terms can separate the effects of the perturbation into a linear component, which is independent of the oldphase at which the perturbation occurs, and a nonlinear component, which is phase-specific. A linear effect could result either from a transient speeding up or slowing down of a central timekeeper or from a fixed interval during which the activity was entirely suspended (in the case of a phase delay), after which it resumed normally. This would constitute a simple dead time, rather than any substantial change in the behavior. The nonlinear effect, however, involves a perturbation's actually altering the form of the cycle in the phase plane, and thus represents a genuine change in the dynamics.

More specifically, linear phase shifts may be due to the constant interval required to switch some general attentional capacity between the responses required for each task.² This response switching could be a part of a time-sharing strategy for combining tasks in a system with limited informational capacity (Broadbent, 1958; 1982). Nonlinear, phase-specific phase shifts, on the other hand, may be due to more complex interference between tasks, such as disruption or degradation of preestablished sets of commands. Thus, comparing the nonlinear fit with a linear fit can capture the more interesting and dynamic effects of task interference, as opposed to the simple time-sharing ones mentioned by Broadbent.

Application to Human Prehensile Movement

The above methods can be applied to substantive issues in motor coordination. As an illustration, consider the combination of hand transport and grasping components involved in everyday prehensile movements, such as reaching out to pick up a glass of water. Three specific issues concerning these movements will be addressed: the separability of reaching and grasping into the operation of two movement systems, assessing the relation between these two processes, and the applicability of PTCs to this relationship.

Reach-and-grasp movements require both that the hand be transported to an appropriate point in space for contacting the object and also that the grasp's opening and closing be appropriate for the intrinsic properties, such as size and mass, of the object to be picked up. They are thus both multieffector and multitask movements.

Jeannerod (1981) has proposed that these two components are performed by independent subsystems: an ego-centric reaching component controlling the transport of the

hand, and an object-centered component controlling the configuration of the fingers for grasping. He suggests that the two components are independent processes that are controlled separately and do not share any information, except for a loose temporal coupling (Paulignan et al., 1990). Two strands of research seem to support this view: First, integrating egocentric and object-centered representations is a complex computational problem (Marr, 1982); second, signals for the control of grasp and of forearm position may be carried in separate tracts in the primate central nervous system (Lawrence & Kuypers, 1968). On the other hand, an architecture of two encapsulated processes is computationally less efficient and less flexible than a model in which the reach and grasp are coordinated to some degree and share information (e.g., Wing et al., 1986; Wallace & Weeks, 1988).

Relations Between Hand Transport and Grasp Aperture

Selective task interference methods are well suited to testing Jeannerod's (1981) hypothesis of two independent processes. If Jeannerod's "two-process" hypothesis is correct, it should be possible to devise perturbations that affect the reach, but not the grasp, and vice versa. Furthermore, the effect of a given perturbation on each movement system should be the same whether the other component is operating concurrently or not; and the effects of a perturbation on the combined reach-and-grasp movement should be predictable from the perturbation's effects on the hand transport and grasp aperture systems in isolation, because the processes are assumed to be independent. For example, if a particular perturbation affects grasping behavior, the two-process view predicts that it should have the same effect on isolated grasping and also on grasping that is part of a composite reach-and-grasp movement. These predictions can be directly tested by comparing the results from complex task-interference and simple task-interference conditions.

In short, studying the differential effects of perturbatory tasks on the components in isolation and in the composite case should be informative about how the reach and grasp components are coordinated and how, if at all, they share information. Furthermore, because timing changes are both known to occur in dual-task performance involving motor control, and to be important to coordination (Allport et al., 1972; Von Holst, 1937/1973), PTC methods seem applicable to the coordination of hand transport and grasp aperture.

Methods

Subjects sat comfortably in a dentist's chair, which allowed unconstrained movements of both arms. The three primary tasks investigated were all cyclic, and all involved the right arm and hand only. They were as follows:

1. Repeatedly grasping a dowel 28 mm in diameter with the right hand, without moving the arm
2. Repeatedly reaching out with the right hand in the horizontal plane over a distance of about 30 cm, without opening or closing the hand

3. Repeatedly reaching and grasping the dowel with the right arm and and, as in a normal prehensile movement

These primary tasks were chosen to involve, respectively, the grasping component alone, the hand transport or reaching component alone, and both hand transport and grasping together. The dowel used in the first and last tasks was located 30 cm in front of the start position, in line with the axis of the subject's right forearm. The dowel was fixed to the work surface with a spring, so it could be grasped, pulled, and released, and would then spring back into the upright position. This arrangement ensured that the third condition, involving combined reaching and grasping movement, approximated normal prehension.

An auditory signal occurred at a random time during each trial. On hearing this signal, the subject performed one of two discrete secondary tasks with the left hand. One secondary task involved grasping a second dowel, again 28 mm in diameter and positioned 30 cm in front of the subject in line with the left forearm. The other secondary task involved reaching out with the left hand in a horizontal plane in front of the body, over a distance of 30 cm. The two secondary tasks were chosen to be similar to the first two primary tasks hypothesized to involve the grasping component alone and the hand transport component alone.

All combinations of the three primary tasks with the two secondary tasks were investigated, giving a total of six conditions. The data from three of these conditions are particularly relevant to the way in which grasping is coupled to hand transport in normal reaching. These three conditions, which are all reported here, involve the effect of a left hand grasp on right hand grasping, the effect of a left hand grasp on right hand reaching, and the effect of a left hand grasp on combined right hand reaching and grasping together. The three remaining conditions, involving the effect of left hand reach on each of the right hand primary tasks, do not

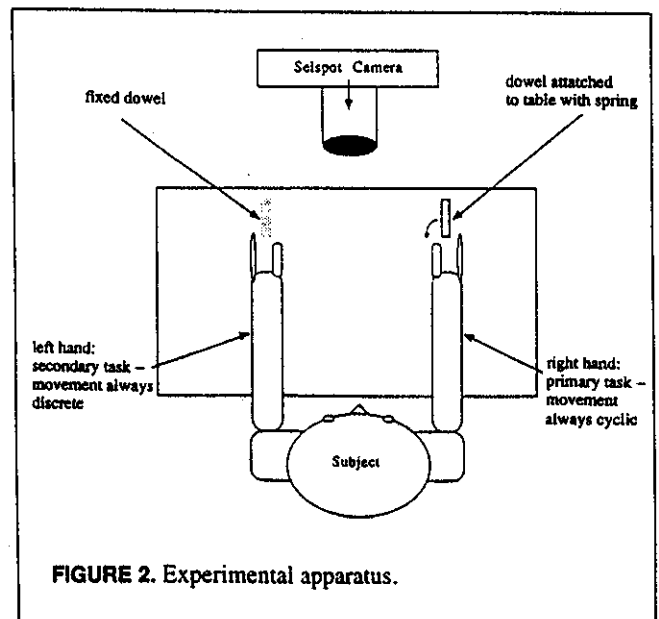


FIGURE 2. Experimental apparatus.

directly address the relation of hand aperture to hand transport, and so are not reported here. An earlier pilot study also included a vocal response as a control secondary task; a condition analogous to Yamanishi et al.'s (1979) Task B. Because this condition, like that of Yamanishi and coworkers, produced no phase shifts at all and made the experimental sessions unacceptably long, it was omitted from the final experiment.

Each condition was planned to include 48 trials, divided into four blocks of 12 trials each. All the trials in a particular block involved the same combination of a particular primary task with a particular secondary task. Subjects were instructed before each block which combination of primary and secondary tasks would be used in that block. One condition for one subject contained only 36 trials, due to error. Furthermore, a very small number of trials that seemed unusable (e.g., because the subject's movement accidentally took the hand outside the workspace) were repeated, so that each block contained at least 12 acceptable trials. The order of the blocks was randomized, with each subject receiving a different random sequence. Each trial lasted approximately 12 s, and was followed by an interval of a few seconds, during which the subject could stop the repetitive movement and relax, if she or he so wished.

Subjects were instructed to perform the primary task at a comfortable speed, which allowed them to make the cyclical movement as regular as possible. They were further instructed to perform the secondary task as rapidly as possible on hearing the auditory signal, while attempting to keep the rhythm of the primary task regular. For the conditions involving grasping, subjects were instructed to grip the dowel between the pads of the thumb and the index finger. Practice was limited to two to three trials per subject, to check that both hands could make the full range of movements involved without being constrained by the apparatus. Because subjects were able to perform the cyclic primary tasks at an appropriate rhythm and to grasp the dowel almost immediately, further practice was judged unnecessary.

The movement of the thumb along the reach axis was monitored using a modified Selspot optical tracking system (accuracy 0.5 mm at 53-cm camera-to-subject distance: Edwards, 1985) positioned above the work surface, and parallel to it. The Selspot camera recorded in two dimensions the positions of infrared-emitting diodes (IREDs) mounted on the distal interphalangeal joints of the right thumb and index finger. Because the thumb showed almost no side-to-side movement during reaching, and because its movement was parallel to the Selspot's y-axis, movement in the y dimension of the IRED mounted on the thumb was taken as the transport component of the movement. The distance between the IREDs on the thumb and index finger in the orthogonal (x) dimension was taken as the grasp aperture component of the movement.

Kinematic data obtained from the Selspot can only give an approximate indication of when the right hand grasps the dowel. Therefore, a surface electrode was attached to the dorsal surface of the subject's right hand, and another to

the dowel grasped by the right hand. The electrodes were isolated from the main supply for safety. Changes in resistance between these two electrodes gave a precise indication of the time at which the subject's right hand contacted and released the dowel.

The data were recorded on FM tape, digitized at 200 Hz, and subsequently processed on a computer. There were 5 subjects. All were right-handed, and were aged between 20 and 30. None had any history of neurological disorders.

Applying and Fitting PTCs

Yamanishi et al. (1979) describe a procedure for finding PTCs by least squares regression fits to sets of data in oldphase and newphase coordinates.

PTC datapoints are phases, so any fit to these points must repeat or "wrap around" on both oldphase and newphase axes, to capture the equivalence of phases across successive cycles. This requirement was satisfied by using a least squares regression with both linear and sinusoidal, nonlinear components. Yamanishi et al. (1979) used a single linear component: a gradient that was fixed at 0 or 1, because these are the gradients underlying all observed PTCs. Their choice of gradient was made by taking the value that gave the best fit, though in other circumstances the choice could be made on a priori grounds, such as magnitude of perturbation delivered. The present study added a further linear component not used by Yamanishi et al. (1979). This was an intercept that could vary freely. Including a linear intercept in the fitting procedure facilitated distinguishing between fixed delays or advances, and phase-dependent phase shifts, as explained above.

The sinusoidal terms are taken in harmonic pairs from the Fourier series:

$$B_k \sin(2\pi kx) + C_k \cos(2\pi kx),$$

$$(k = 1 \dots n),$$

where B_k and C_k were coefficients that could vary freely.

Whereas Yamanishi et al. (1979) were primarily interested in the gross distinction between Type-0 PTC and Type-1 PTCs, more subtle distinctions can be made between fitted PTCs of the same type. Thus, the incremental F statistic can be used as described above to compare the quality of fit using just linear terms with the quality of fit using linear terms plus some sinusoidal, nonlinear terms intended to capture the effect of the perturbation. This statistic will be called the *nonlinear versus linear incremental F*. In this study, the fitting procedure was restricted to use only the first and second pairs of harmonics as the nonlinear terms, because these seemed to capture the pattern of phase shifts in the data without consuming too many degrees of freedom in the regression.

Thus, the equation of the nonlinear regression fitted was:

$$y = Mx + A + B_1 \sin(2\pi x) + C_1 \cos(2\pi x) \\ + B_2 \sin(4\pi x) + C_2 \cos(4\pi x),$$

where y = newphase, x = oldphase, and $M = 1$ (because the "perturbations" delivered were not highly disruptive).

The first, second, and third transient PTCs were calculated for each subject in each condition using this equation. Transient PTCs after the third were not calculated because the movement generally returned to stable oscillation within three cycles. The issue of which nonlinear terms should be used is considered again in the methodological discussion.

Results

Kinematics of Waveforms

Figure 3 shows typical time series waveforms for the transport and aperture components of a right hand combined reaching and grasping movement during one trial. The upper waveform represents the movement of the thumb in the y dimension, and can be taken as the hand transport component of the behavior. The valleys of the lower waveform represent the starting position, whereas the peaks represent the position of the hand while grasping the dowel. The amplitude of the upper waveform, given by the valley-to-peak displacement, averages about 30 cm. The lower waveform represents the distance between the finger and thumb IREDS in the x dimension, and can be taken as the grasping component of the behavior. The valleys of the lower waveform represent a closed grasp, whereas the peaks represent the maximum aperture attained just before grasping the dowel. The valley-to-peak displacement averages about 8 cm. The "notch" or horizontal portion just after maximum aperture represents the time during which the subject grasped the dowel with the right hand, while pulling it slightly backwards. Contact between the right

hand and the dowel on the first cycle is marked by the first vertical dashed line.

The regular, cyclic nature of both waveforms can be seen clearly. Further, the two waveforms appear to be synchronized throughout the trial. The secondary task following the auditory signal or "perturbation," marked on Figure 3 by a further vertical dashed line, was a discrete left hand grasp. The secondary task appears to have little effect on the timing of key events in the grasp waveform such as grasp contact (cf. Figure 7). The kinematics of the grasp waveform for this trial seem to show a slight increase in maximum grasp aperture immediately after the perturbation, however. Whereas kinematic variations do not come within the scope of the present analysis using PTCs, the possibility of kinematic effects deserves further study.

Phase Transition Curves

The results were analyzed using PTCs, in order to assess the effects of the secondary tasks on the various primary tasks. Different events are used to define Phase 0 for different experimental conditions. Where the primary task was repetitive right-handed reaching, Phase 0 represents the instant of the peak forward velocity of the right thumb as it approached the dowel. In these conditions, grasping the dowel generally occurs around Phase 0.3, and the start of the forward transport of the hand toward the dowel generally occurs around Phase 0.8. Where the primary task was right-handed grasping alone, or combined reaching and grasping, Phase 0 represents the instant of the subject's hand contacting the dowel, as determined from the resistance between the electrodes on the hand and the dowel.

Figure 4 shows a typical set of data points for Subject 5 in the first condition: the effect of a left grasp perturbation on an isolated right-handed grasp. The first, second, and third transient newphase values are plotted against the oldphase values, with the first transient at the bottom of the graph and the third at the top. Although the newphase is measured modulo 1, a constant of 1 has been added to all the second transient newphase values, and a constant of 2 to all the third transient newphase values, to separate each set of newphase values for display purposes. The solid curves, from bottom to top, are the first, second, and third transient PTCs, fitted to each set of data points using the equation given above. The dashed lines all have a gradient of 1 and, from bottom to top, intercepts of 0, 1, and 2. These are respectively the first, second, and third transient PTCs, which would have been obtained if the perturbatory task had had no effect on the timing of the primary task. The distance between the solid and the dashed line represents the overall effect of the perturbation, whereas the variations of curvature in the PTCs (solid lines) represent the nonlinear, phase-specific effect of the perturbation. More disruptive perturbations would tend to produce PTCs with a high mean displacement from the line of no perturbation, and with high curvature.

The data shown in Figure 4 are clearly better fitted by a PTC with an underlying gradient of 1 than by a PTC with

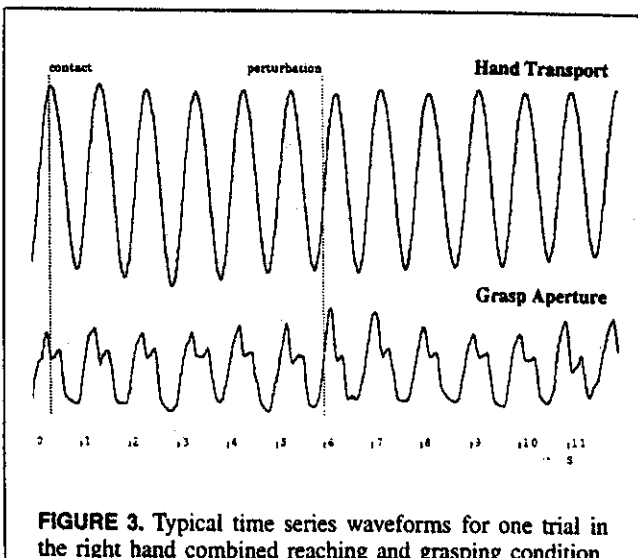
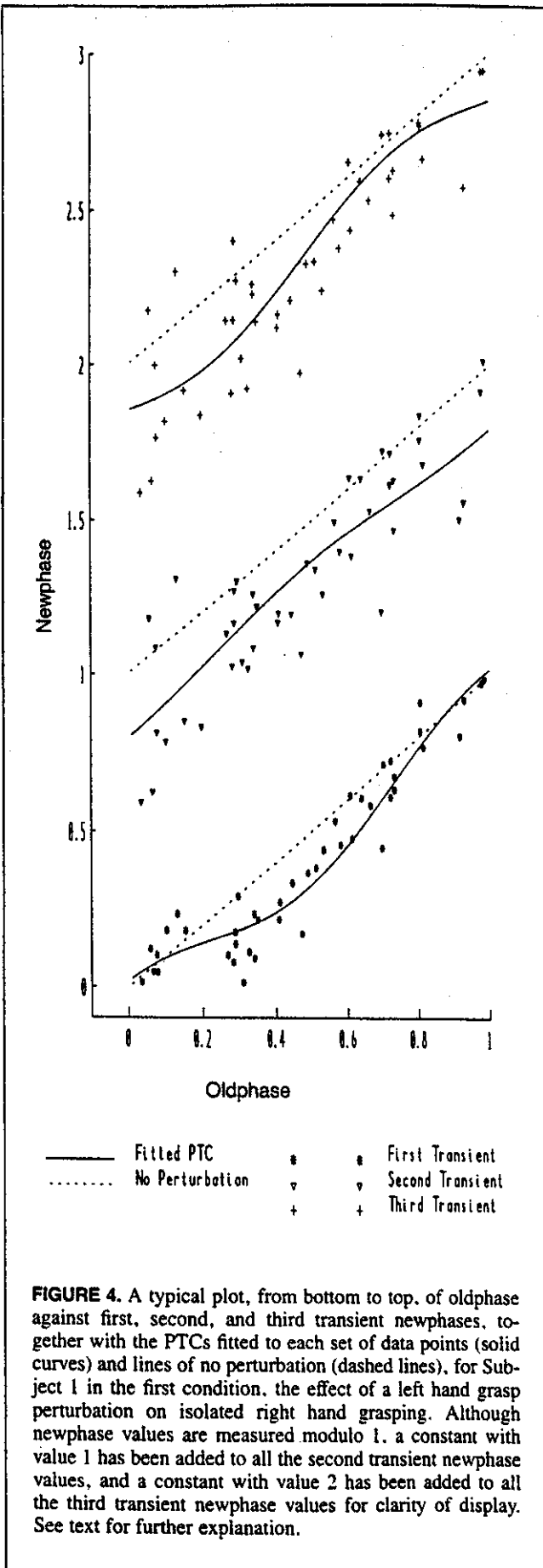


FIGURE 3. Typical time series waveforms for one trial in the right hand combined reaching and grasping condition. The upper trace shows the position in the y dimension of an infrared emitting diode (IRED) mounted on the distal joint of the right thumb. The lower trace shows the distance in the orthogonal, or x , dimension, between the IREDS mounted on the right thumb and the right finger. Note the clear periodic nature of both waveforms.



a gradient of 0. On the other hand, the data points do deviate from a simple linear model with unit slope and zero intercept. This is particularly evident from the first transient of the data shown in Figure 4: Note the concavity of the first transient PTC and the displacement of the data points below the line of no perturbation around oldphase values 0.2 to 0.8. This contrasts with the much smaller displacements from the line of no perturbation for oldphase values from 0.8 to 0.2. If the requirement to make a left hand grasp occurs in the former section of the right hand's grasp cycle, the effect is a phase advance, whereas in the latter section of the cycle, the perturbatory task appears to have little or no effect. The effect of the discrete secondary task on the cyclic movement is thus clearly nonlinear, and the characteristics of the nonlinearities can be captured by the sinusoidal terms of the PTC.

The overall pattern of PTCs obtained is shown in Figures 5 to 7. The nonlinear versus linear incremental F s for the first transient PTCs shown in these figures are given in Table 1. Taken together, the combination of simple and complex task-interference results expressed in these figures suggests that the two-process theory of reaching and grasping must be incorrect.

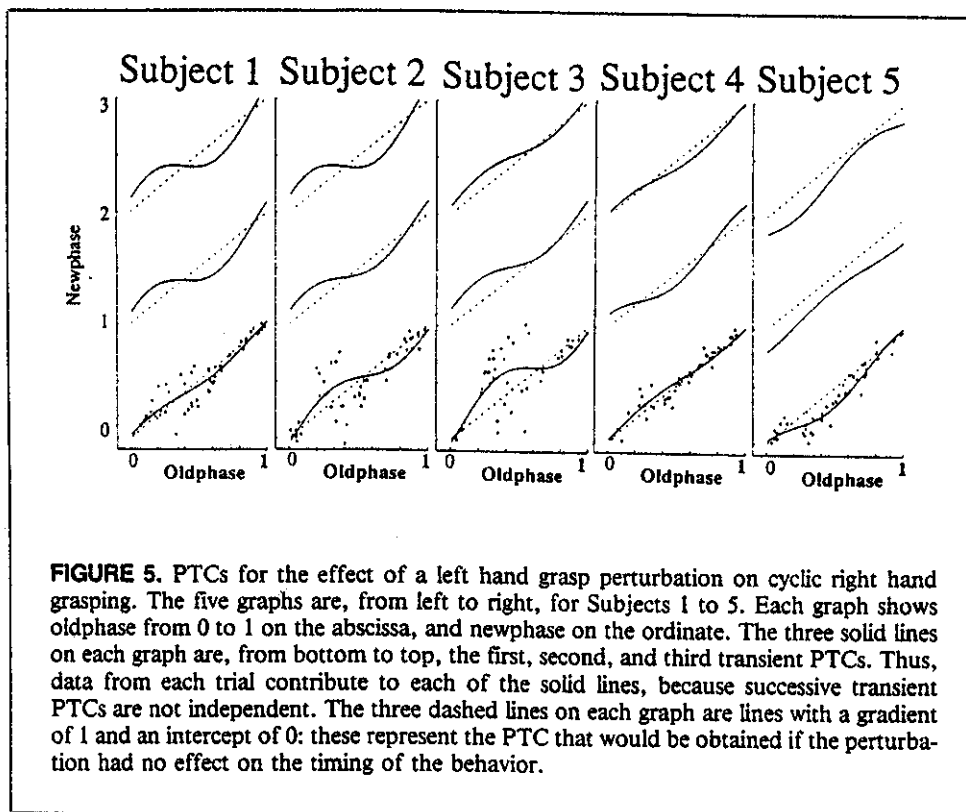
Considering the first transient PTC only, the left-handed grasp perturbation significantly disrupted right hand grasping in most subjects (see Figure 5). In this figure, PTCs for Subjects 1 to 5 are presented from left to right. For each subject, the fitted PTCs and lines of no perturbation are arranged exactly as in Figure 4. Subject 5's data, already seen in Figure 4, are therefore shown again as the plot on the right. The individual data points, each representing one trial, are shown for the first transients but have been omitted for the second and third transients, for purposes of clarity. When compared to a linear fit with gradient 1 and variable intercept, the nonlinear fits for the first transient PTC gave values for the incremental F statistic that were significant at the 5% level, indicating a significant effect of the perturbatory task for each subject except Subject 3. The nonlinear pattern is also clear from visual inspection: A perturbation occurring between oldphase values 0.2 and 0.8 caused substantial displacements from the line of no perturbation in all 5 subjects' data. Perturbations occurring between 0.8 and 0.2, by contrast, do not appear to produce large phase shifts. For this condition, the "reference event" corresponding to Phase 0 of the primary grasping task was the time of first contact between the subject's right hand and the dowel.

The same left hand grasp perturbation did not perturb right hand reaching as much (see Figure 6), however. None of the nonlinear versus linear incremental F s for the first transient PTCs in Figure 6 are significant, showing that the grasp perturbation did not disrupt the right hand's reaching behavior. The reference event corresponding to Phase 0 in this condition was the peak velocity of the right thumb along the reach axis during the approach to the dowel.

These two results may be seen as an instance of like tasks interfering more than unlike tasks (cf. McLeod, 1977).

TABLE 1
Nonlinear Versus Linear Incremental Fs for First Transient PTCs Shown in Figures 5-7

Corresponding figure	Figure 5	Figure 6	Figure 7
Primary task (cyclic, right hand)	Grasp	Reach	Combined reach and grasp
Secondary task (discrete, left hand)	Grasp	Grasp	Grasp
Subject 1	Inc. $F(4, 43) = 4.53, p < .001$	Inc. $F(4, 55) = 1.37, N.S.$	Inc. $F(4, 43) = 6.63, p < .001$
Subject 2	Inc. $F(4, 42) = 7.48, p < .001$	Inc. $F(4, 43) = 0.73, N.S.$	Inc. $F(4, 31) = 2.03, N.S.$
Subject 3	Inc. $F(4, 41) = 1.59, N.S.$	Inc. $F(4, 42) = 1.83, N.S.$	Inc. $F(4, 45) = 0.82, N.S.$
Subject 4	Inc. $F(4, 38) = 2.83, p < .001$	Inc. $F(4, 38) = 1.24, N.S.$	Inc. $F(4, 38) = 1.84, N.S.$
Subject 5	Inc. $F(4, 40) = 6.93, p < .001$	Inc. $F(4, 43) = 0.85, N.S.$	Inc. $F(4, 45) = 1.80, N.S.$

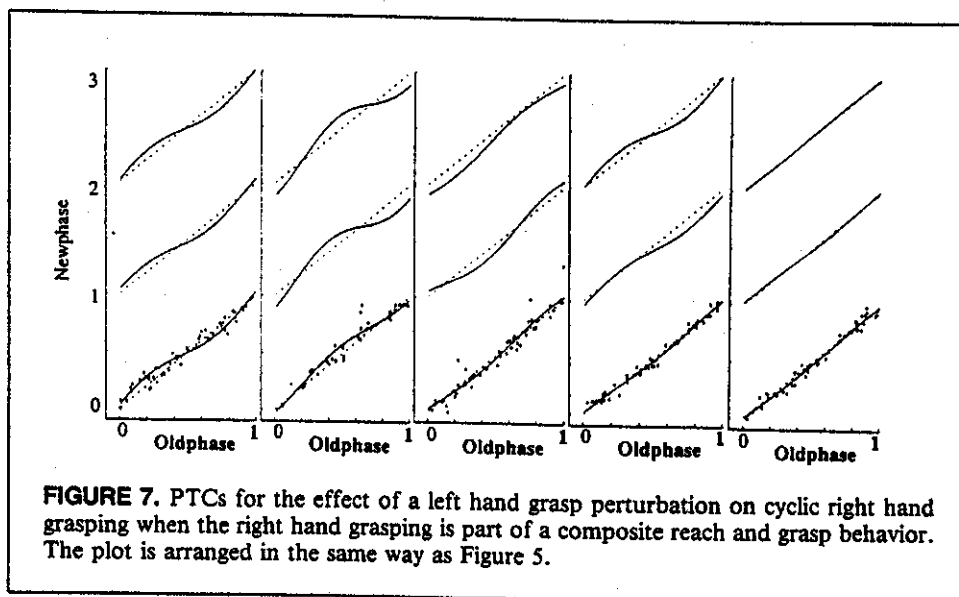
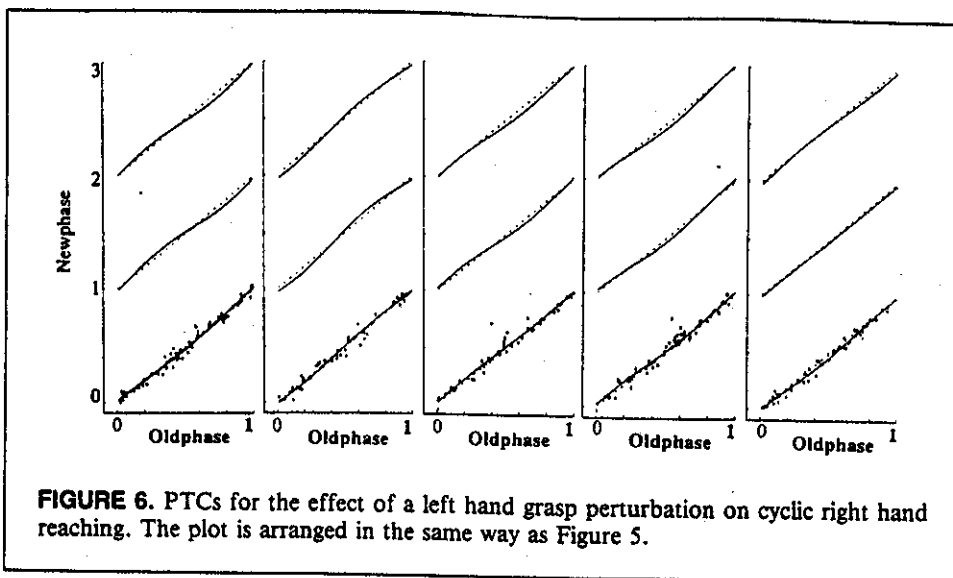


Such effects of task similarity are restricted to the case in which both tasks are performed in isolation, however, and do not hold for complex reaching and grasping. In the case of complex movements, the two-process view predicts that the left grasp perturbation should perturb a right hand grasp even when the latter component is combined with a reach in a composite reach-and-grasp movement, because the effects of perturbations on the composite movement should derive straightforwardly from the effects on the component movements when performed in isolation. The PTCs of Figure 7 show that this is clearly not the case. As in Figure 5, the reference event corresponding to Phase 0 of the primary grasping task was the time of first contact between the subject's right hand and the dowel. None of the nonlinear versus linear incremental Fs for the first transient PTCs in Fig-

ure 7 are significant, except those for Subject 1. Thus, for most subjects, the left grasp perturbation did not severely disrupt the right hand's grasping when this was part of a composite reach-and-grasp movement. Note particularly that the first transient PTCs of Figure 7 exhibit much less curvature than those in Figure 5, and the data points are less scattered around the line of no perturbation, indicating that the effect of a left hand grasp perturbation on cyclical right hand grasping is less when the right hand's grasping movement is a component of a combined prehensile movement than when grasping is performed alone.

DISCUSSION OF RESULTS

In the composite case, where the right hand grasp is part of a normal reach-and-grasp behavior, the grasp is no



longer susceptible to perturbations that do have an influence when grasping is performed in isolation. The attempt at selective perturbation of the grasp aperture component alone therefore fails in the composite case. This suggests that the co-occurrence of the right hand's reach causes a fundamental alteration in the way the right hand's grasping movement is controlled. Specifically, in the composite movement, the control of the grasp seems functionally dependent on the control of the reach. This result is inconsistent with any theory that proposes independent control of hand transport and grasp aperture.

An alternative interpretation of this result might attribute the lack of phase shifts in Figure 7 to the fact that more time is available to organize the right hand's grasp when this is part of a composite reach-and-grasp movement, because in the complex, but not in the isolated condition, grasping takes only a proportion of the total time required for the movement. Thus, the grasp could be planned in ad-

vance, during this spare time, and the motor program simply run off at the appropriate instant. Adequate buffering of this kind might ensure that a discrete perturbation will not produce interference. Although this interpretation cannot be ruled out on the basis of the present data, it seems implausible for two reasons. First, preplanning the grasp movement during any spare time before grasping actually occurs might produce an unacceptably large number of movements in which the grasp was not well adapted to the characteristics of the reach, and therefore of errors in grasping the dowel. Almost no such errors were observed. Second, in repetitive tasks such as those reported here, subjects would presumably tend to plan the grasp at approximately the same point in each composite movement. But, because perturbations were delivered randomly over all phases of the movement, a tendency for greater phase shifts on trials where the perturbation occurred around this point would be expected. No such tendency is apparent in Figure 7.

The qualitative similarity of the first, second, and third transient PTCs for each subject in each condition is also noteworthy. In particular, if a perturbatory task causes a phase-specific advance or delay (i.e., concavity or convexity of the PTC) for the first transient, the same pattern generally appears in the second and third transients, though perhaps to a slightly lesser extent. Thus, where a secondary task does disrupt the phase of the primary task, this disruption seems to be permanent: There is no systematic modulation of the timing of subsequent cycles of the primary task in order to return to the preperturbation phase. Rather, the perturbation permanently shifts the whole postperturbation time series.

The differential penetrability of component tasks when interfering tasks are performed concurrently has been used to study the coordination of those components into a complex everyday movement. Because it is possible to reach without grasping and vice versa, the composite movement can presumably be "parsed" into a transport task and a grasp configuration task. These two components seem to be combined in a way that shares information, however, because the effect of a grasp perturbation on the composite movement cannot be predicted from the effects on the transport and aperture components independently. So a model that treats ordinary reaching and grasping as the addition of two entirely independent and encapsulated tasks is inadequate. Rather, the control of transport and aperture seems to be organized in a hierarchical, rather than a parallel fashion, because the co-occurrence of a reach with a grasp resulted in a pattern of perturbability that is similar to that for a reach, rather than some compromise between the patterns for hand transport and grasp.

METHODOLOGICAL DISCUSSION

A combination of task interference and PTC methods has previously been used by Yamanishi et al. (1979). They obtained PTCs for the effects on cyclic finger tapping of three discrete, secondary tasks: a visual cognition task, a vocal reaction task, and a key pressing task performed with the contralateral hand. The key pressing task caused the greatest phase shifts in the rhythm of finger tapping, and thus was judged most disruptive. Yamanishi and colleagues' main interest was in the processes underlying timing control of the cyclic finger-tapping movement of the dominant hand. By introducing a variety of concurrent tasks as "perturbations," they were able to introduce a resetting of the timekeeper or clock underlying finger tapping. This resetting was attributed to a change in processing, such as a delay in the neural mechanism responsible for timing control, caused by the perturbatory task. Whereas Yamanishi et al. (1979) investigated timing of a movement with only a single clear component, the present approach expands their methods to use PTCs and task interference to investigate coordination of multiple component tasks, such as the integration of hand transport and grasping in prehensile reaching movements, using selective perturbation techniques.

Possible Effects on the Secondary Task

The effects of interference on the discrete, secondary task merit consideration. Yamanishi et al. (1979) showed that the reaction times in their secondary tasks were independent of the oldphase. They therefore argued that the phase-specific resetting of the cyclic tapping task could not be attributed to a simple pause required for the performance of the secondary task. The present study assumed, following Yamanishi et al. (1979), that reaction time for the discrete, secondary task would constitute a phase-independent "dead time," producing a simple linear phase-resetting. Thus the nonlinear versus linear incremental F statistic used automatically takes account of the reaction time component of the task interference by the discrete, secondary task, because the linear fit already includes an intercept term. In addition, the mean phase-resetting of the continuous, primary task introduced by the discrete, secondary tasks in this study was often very small (e.g., Figure 6), implying that the effects of interference on the timing of the discrete task may also be negligible.

The approach taken in this study and in that of Yamanishi et al. (1979) contrasts with Posner and Boies' (1971) probe reaction time paradigm. Posner and Boies emphasized the performance of the discrete, secondary task and ignored any disruption it might have caused to the continuous, primary task. Their justification is interesting in the current context: "In studying movements, it was found that the probe had little effect on the primary movement task, but that the probe RT reflected the central processing demands of the primary task in a very sensitive way" (p. 401). Logical difficulties in using secondary task performance as a reliable and independent index of primary task control (Brown, 1968; Duncan, 1979) raise problems for probe reaction time studies, however. The alternative approach, as taken in this study, retains the concern with quantifying control throughout the movement but emphasizes the effects of interference on the continuous, primary task, rather than on the discrete, secondary task. Thus, whereas Posner and Boies did not deliberately match primary and secondary tasks, the present technique specifically chooses discrete, secondary tasks with a view to their possible effects as selective perturbations of the primary movement.

Further Issues Regarding PTCs

A study by Kay (1986) used PTCs to assess the effects of a brief mechanical perturbation from a torque motor on human finger movements. Kay used the pattern of phase shifts induced by the perturbation to investigate the dynamics of the oscillator presumed to underly the movement. One problem in using mechanical perturbations may be the change in displacement of the effector caused by the torque motor, which can itself generate a reference event, thus artifactually producing an abnormally long or short "cycle," which is purely passive. Perhaps for this reason, Kay chose to use steady-state PTCs only.

Both Yamanishi et al. (1979) and Kay (1986) presented their perturbations at phases of the movement (oldphases)

that were determined by an on-line measuring device. Yamanishi et al. (1979) perturbed at oldphase values 0.0, 0.1, . . . 0.9. Kay aimed to perturb at oldphase values 0.0, 0.25, . . . 0.75, though he did subsequently calculate the precise oldphase from the movement waveform. This practice of perturbing only at or around particular oldphase values seems unfortunate in two respects. First, it makes perturbations statistically more predictable. Second, it has adverse consequences for curve fitting. Clustering perturbations on specific oldphase values requires fitting a predominantly diagonal (Type 1) or horizontal (Type 0) PTC to a few vertical bars of data points. Not only is the detailed representation of phase shifts in the regions between the bars entirely lost, but the results of fitting sinusoids to such "vertical" data sets can be deceptive. A statistically more acceptable approach is to deliver perturbations entirely randomly, without on-line monitoring and control of oldphase values. Where the number of trials is large, scatter of the data over all oldphase values is guaranteed. This latter approach is also technologically simpler.

The use by Kay (1986) and by Yamanishi et al. (1979) of steady-state, rather than transient, PTCs raises two distinct problems. Whereas steady-state PTCs are better understood, their use implies discarding information about the behavior's transient response to perturbation. For example, if the newphase values for a particular set of oldphase values exhibit a pattern of oscillation between successive transients (such as a phase delay for the first transient, and a phase advance for the second), this would be equivalent to a negative autocorrelation at a lag of unity (Wing & Kristofferson, 1973). Because the first, second, and third transient PTCs for the reaching and grasping data reported above are qualitatively similar, the processes responsible for the negative lag 1 autocorrelations found in other rhythmic movement time series, such as tapping, appear to be absent from the prehensile movements observed in this study. This difference merits further investigation.

Further, the precise time taken for return to the steady state could vary substantially from one trial to the next and could also vary as some interesting function of the magnitude of the perturbing stimulus, or of the oldphase. This information, which may be relevant to the system's dynamics under perturbation (Scholz & Kelso, 1989), is similarly discarded when using steady-state PTCs.

Finally, the problem of fitting PTCs deserves a few further comments. The regression procedure proposed by Yamanishi et al. (1979), which involves a linear plus sinusoidal least squares fit, clearly satisfies the requirement of a biperiodic regression. A number of difficulties remain, however. First, sinusoidal fits inevitably tend to obscure any interesting local discontinuities in PTCs. As such discontinuities have been found in some biological systems (though not yet in human movement), this may be an unfortunate omission. Second, each additional pair of regression terms taken from the Fourier expansion transfers two degrees of freedom from the denominator to the numerator. Thus, greater statistical significance for a fit to a set of data

points may sometimes be achieved by reducing the number of sinusoidal terms. This is particularly the case where there are few data points. Fitting too few sinusoidal terms may yield significance at the price of failing to capture the actual pattern of phase shifts in the data. On the other hand, using a larger number of sinusoidal parameters, thus including some of higher frequency, will give a more detailed fit to any confined regions on the abscissa where there are phase shifts that are highly phase specific, in the sense that the response of the system to perturbation may be very highly dependent on the oldphase at which the perturbation is delivered. The interesting possibility of identifying such behavior in human movement control encourages the use of a fair number of sinusoidal terms.

CONCLUSIONS

The methodological section of this paper has argued for the value of both phase transition curves and task interference techniques in studies of coordinated movement and has discussed some modifications and extensions to these methods with a view to increasing their applicability. The experimental section has used these methods to suggest a functional linkage between grasp aperture and hand transport in human prehension.

NOTES

1. Phase transition curves are an analytical technique, rather than a behavioral observation, and bear no relation to the "phase transition" phenomenon observed by Kelso (1984) in human cyclical movement.
2. Evidence from other fields confirms the linear nature of time-sharing and switching effects. Yoshizawa and Takeda (1988) accounted for performance on a continuous pursuit tracking task using "an inherent dead time included in the operator." Miall et al. (1985) also posited feedback delays to explain intermittencies in monkeys' visuomotor tracking.

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