## RESEARCH ARTICLE

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# Discrete and cyclical units of action in a mixed target pair aiming task

**Abstract** Two experiments addressed the issue of discrete and cyclical units as possible basic units of action that might be used to construct complex actions based on task constraints. The experiments examined the influence of low and high accuracy constraints on the end-effector's motion in rhythmical aiming movements. Both experiments utilized a Fitts-type task under three accuracy constraints: (1) big target pairing—low index of movement difficulty (ID), (2) small target pairing—high ID, and (3) mixed target pairing—one target high ID and the other target low ID. Experiment I was a 1-degree-of-freedom (*df*) task that required subjects to crossover the inside edge of targets in a target pair using elbow flexion–extension motions. Experiment II used a 2-*df* task that required subjects to tap back and forth between targets in a target pair using a hand-held stylus. In both experiments, end-effector motion in the low ID condition was cyclical with the end-effector's motion consistent with a limit-cycle attractor description, while in the high ID condition end-effector motion was discrete and consistent with a fixed-point attractor description. The mixed target pairing produced both discrete and cyclical features in the end-effector's dynamics that suggested a functional linking of discrete and cyclical units of action as the optimal movement solution. Evidence supporting the above statements was found in the kinematic measures of movement time (MT), dwell time, proportion of MT accelerating and decelerating, and in a measure of harmonicity (Guiard 1993, Acta Psychol 82:139–159; Guiard 1997, Hum Mov Sci 16:97–131). Extended practice in the mixed target condition revealed a bias towards cyclical motion with practice. The results demonstrate that discrete and cyclical motion, represented as limit-cycle and fixed-point attractors, are basic units of action that the motor system uses in constructing more complex action sequences. The results are discussed with reference to coordinative structures and the generalized motor program as basic units of action. Issues pertaining to visual feedback processing and movement braking in rapid aiming tasks are also discussed.

**Keywords** Motor control · Dynamical systems · Fitts' law · Harmonicity · Accuracy constraints

## Introduction

Dichotic classification schemes have played a predominant role in how researchers classify and study movements, develop control structures, and formulate theoretical perspectives. For example, an extensive amount of motor control research literature may be classified as an investigation of discrete motion with a well-defined start and end point (e.g., aiming or reaching), or as the investigation of cyclical motion defined by the repetitive action of one or more limbs (walking, swimming). This dichotomy of discrete versus cyclical motion has dominated the formulation of theoretical perspectives in the field. Discrete movement studies tend to take center stage in the development of many information-processing models (Schmidt et al. 1979; Meyer et al. 1988; Plamondon and Alimi 1997; Schmidt et al. 1998), while cyclical movements are paramount to the development of coordination dynamic models (Turvey 1990; Kelso 1995). Many motor skills, however, consist of both cyclical and discrete motions, especially, when several limbs or joints must be coordinated. This suggests that discrete and cyclic motions are represented as independent units of action that can be functionally linked to build complex motor skills (Sternad et al. 2000). Recently, the problem of the how the central nervous system may control discrete and cyclical motions of the same limb simultaneously has been addressed with cyclical movement tasks (Adamovich et al. 1994; Sternad et al. 2000; Staude et al. 2002). Building on this idea, we raise the question: how might the central nervous system control discrete and

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cyclical motion in repetitive aiming when the task creates a competition between discrete and cyclical solutions?

Central to information-processing and dynamical systems approaches is the notion of a basic unit of action, i.e., the most fundamental unit of control for assembling complex skilled actions (Guiard 1993; Kelso 1994; Schmidt et al. 1998). A primary assumption of the information-processing view is that a complex movement, whether discrete or cyclical, is assembled through the concatenation of discrete motor primitives (Meyer et al. 1988). Repetitive and non-repetitive aiming tasks have been used extensively as an experimental technique to study how discrete motion primitives are assembled (or programmed) into more complex movement sequences (Adam et al. 1995; Rand et al. 1997; Lajoie and Franks 1997; Rand and Stelmach 2000). Over the past 50 years, much of the work using either repetitive or non-repetitive tasks has focused on what has come to be known as "Fitts' law" (Fitts 1954); for review (Meyer et al. 1988; Plamondon and Alimi 1997). The basic premise of Fitts Law is that movement-amplitude ($A$) and target-width ($W$) interact to define an index of movement difficulty, $ID=log_2(2A/W)$ (Fitts 1954). Due to the fixed nature of the motor system's transmission capacity as espoused by Fitts, any change in ID is systematically related to movement time (MT) as follows, $MT=A+B(ID)$. The most prominent information-processing models of rapid aiming that capture Fitts' Law are built upon the principle of concatenation of discrete primitives, e.g., the intermittent feedback hypothesis (Crossman and Goodeve 1963; Keele 1968), the multiple submovement model (Meyer et al. 1988), and the kinematic model (Plamondon and Alimi 1997). A primary difference in the above models is the role that open-loop and closed-loop processes, especially visual processes, play in the concatenation process (Plamondon and Alimi 1997; Ricker et al. 1999; Cullen et al. 2001; Elliott et al. 2001).

From the dynamical system perspective, many models are developed from nonlinear oscillators that capture many features of cyclical motion, and discrete motions are modeled as a limiting case of cyclical motion that emerges when the motor system must perform under highly constrained conditions (Schöner 1990; Kelso 1992; Guiard 1993). Recently, modeling accounts of repetitive aiming tasks in line with the coordination dynamics perspective have been proposed to explain the systematic slowing of movements associated with increasing accuracy demands (Guiard 1993, 1997; Mottet and Bootsma 1999). As a starting point, the end-effector's trajectory is analyzed in terms of phase-plane (displacement-velocity) and Hook portraits (displacement-acceleration) in order to reveal stable reproducible behavioral states in the system's dynamics. This type of initial quantitative approach is referred to as a topological analysis and seeks to map the observed reproducible behavioral states onto stable attractors (fixed-point, limit-cycle, etc.) of some dynamical system (Kugler et al. 1980; Beek and Beek 1988). As a result of this topological approach, Mottet and Bootsma (1999) modeled the end-effector's

dynamics in a repetitive aiming task (ID range from 3 to 7) as stable limit-cycle motion of a nonlinear oscillator, without resorting to the concatenation of discrete movement primitives. The cyclical or discrete nature of the end-effector's dynamics in a repetitive aiming task may also be measured with an index of harmonic motion (H), which characterizes the presence or absence of inflection points in the acceleration trace when a movement reversal occurs (Guiard 1993, 1997). Using repetitive and non-repetitive aiming tasks, it has been shown that H=1 represents simple harmonic motion and H=0 represents discrete motion, with the demarcation point between discrete and cyclical motion (H=0.5) occurring for IDs in the range 4 <ID <5 (Guiard 1997).

Another way to approach the issue of discrete versus cyclic units of action is to exploit tasks that require the simultaneous production of discrete and cyclical movements with the same limb (Adamovich et al. 1994; Sternad et al. 2000; Staude et al. 2002). In these simultaneous production tasks, subjects may be asked to oscillate a joint like the elbow, about a certain degree of extension, e.g., 100° extension, and then shift the oscillation to another position, e.g., 50° of elbow extension. Under these conditions, the discrete motion is the shift in oscillation point of the elbow from 100° to 50° of extension. Although arriving at different conclusions regarding whether the discrete and cyclical commands are issued in sequence (Adamovich et al. 1994) or simultaneously (Sternad et al. 2000), the authors clearly resonate to the idea that discrete and cyclical motion represent basic movement primitives or units of action. This idea of separate units of action for discrete and cyclical motion is consistent with the two basic attractors of a nonlinear dynamical system: (1) a fixed-point attractor, and (2) a limit-cycle attractor, respectively. This conceptualization led Sternad et al. (2000) to develop a model of interacting-point and limit-cycle attractor dynamics to account for simultaneous discrete and cyclical motion in the same limb.

The two experiments presented here are designed to investigate how the motor system plans and modifies the end-effector's trajectory when the targets in a repetitive aiming task create a competition between discrete and cyclical solutions as the optimal solution. Thus, the goal is to see whether one type of control structure, fixed point or limit cycle, will dominate in a Fitts-type task with targets of different IDs (Sidaway et al. 1995; Adam and Paas 1996; Smyrnis et al. 2000). Pairing low and high ID targets creates a competitive situation in which the optimal solution for the low ID target is a cyclical solution (Fig. 1A), while the optimal solution for the high ID target is a discrete solution (Fig. 1B). The cyclical solution is characterized by short movement times and rapid movement reversals over the target (short dwell times) with an equal proportion of movement time spent accelerating and decelerating. Thus, the low accuracy constraint allows for a simple harmonic solution (H=1) to the task (Guiard 1993). The discrete solution is characterized by long movement times with the arm coming to
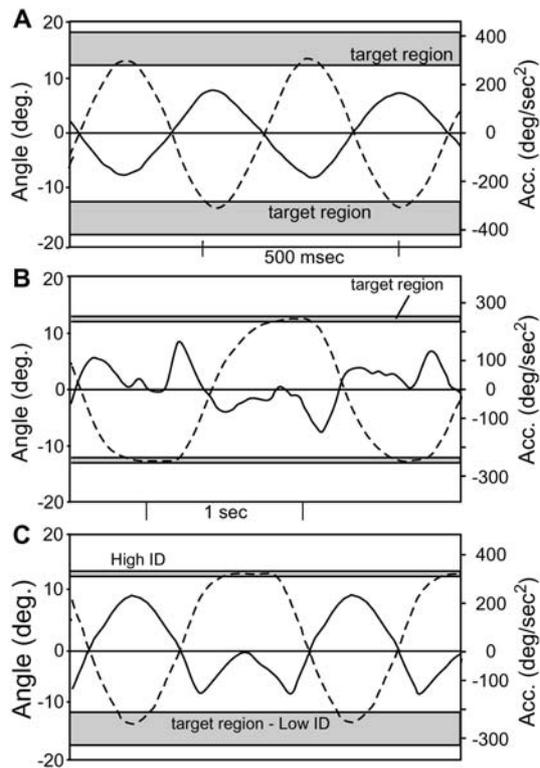
**Fig. 1A–C** Examples of position (*dashed lines*) and acceleration (*solid lines*) time-series from a repetitive aiming task. **A** is from a low index of movement difficulty (ID 2.4) condition. **B** is from a high ID (5.85) condition. Based on hypothesis 3 (see text for details), **C** is a constructed representation of the possible outcome when the low and high ID targets are paired. Movement reversals occur over the target represented by the *shading*

an equilibrium point (acceleration =0, velocity =0) over the target (long dwell times) before a movement is initiated in the opposite direction. In this case, the movement is inharmonic (H=0) (Guiard 1997) and a greater proportion of movement time is spent decelerating than accelerating, suggestive of more time for visually based feedback guided adjustments (Heath et al. 1998; Ricker et al. 1999; Cullen et al. 2001).

Non-repetitive 2-stroke versions of the mixed target pair task have been used to study motor planning and organization in aiming (Adam et al. 1995; Rand et al. 1997; Lajoie and Franks 1997; Rand and Stelmach 2000). Rand and Stelmach (2000) argued that a higher ID on the first target compared to the second target leads to motor planning in terms of two independent discrete segments, one for each target. The higher ID target appearing first in the sequence did not provide a context-dependent kinematic relationship that would allow the segments to be chunked. When the first target has a lower ID than the second target, the motor system is able to chunk the segments into a functional unit (Adam et al. 1995; Rand et al. 1997). Chunking is possible because the low ID condition appearing first in the 2-stroke sequence provides a context-dependent kinematic relationship, allowing the motor system to consider features of both

segments in determining the kinematics of the sequence (Rand and Stelmach 2000). Competition in this 2-stroke task led to unique solutions in terms of chunked segments or independent discrete segments. Regardless of the end solution, chunked or discrete, the initial starting point was from discrete motion primitives. The use of a mixed target pair in a repetitive aiming task produces a similar competition to the 2-stroke task, but allows for an extension since the repetitive motion allows for cyclical solutions to emerge as well as discrete solutions. This will provide an opportunity to examine the chunking process in terms of parameterizing a nonlinear dynamical system such that limit-cycle dynamics (cyclical motion) are functionally linked to point-attractor dynamics (discrete motion) and vice versa.

A repetitive aiming task consisting of a target pair constructed from low and high ID conditions allows for the formulation of three hypotheses regarding the competition between discrete and cyclical solutions. First, if discrete and cyclical motions are assembled from discrete primitives, then the mixed target pairing should reduce the cyclical motion to the large target (Fig. 1A) to a discrete primitive with the task solution being the concatenation of discrete primitives. This should lead to equilibrium points on the low ID target with longer dwell times, acceleration and velocity zero, and harmonicity zero. Second, if the cycle is the fundamental unit of action, then the mixed target pairing should produce some form of limit-cycle oscillation. This would be reflected in similar dwell times for the different sized targets, proportionally equal acceleration and deceleration times to each target, the disappearance of the equilibrium point over the high ID target (Fig. 1B), and a harmonicity value approaching 1. Third and lastly, if discrete and cyclical motions are independent units of action, then the mixed target paring should lead to a functional linking of these units to meet task demands. In this case, the end-effector's trajectory should contain features of both discrete (fixed-point) and cyclical (limit-cycle) motion as a function of target ID. This might occur as follows: maximum acceleration with movement reversal over the low ID target and equilibrium points over the high ID target, H values of around 0.5, with the acceleration–deceleration profiles different to each target (Fig. 1C). We propose that the third hypothesis listed above will be observed and supported with kinematic measures of acceleration–deceleration time, dwell time, and end-point trajectory harmonicity. As a final point, research has shown that practice in repetitive aiming tasks can lead to significant reductions in movement time and changes in the acceleration profile of the end-effector (e.g., Fischman and Lim 1991; Pratt et al. 1994; Pohl and Winstein 1998). To study how the end-effector's dynamics might be modified over time in this competitive situation, extended practice was given in the mixed target task. The above hypotheses are tested with a 1-degree-of-freedom elbow flexion–extension task in experiment I and with a 2-degrees-of-freedom tapping task in experiment II.

## Experiment 1

Materials and methods

### Subjects

The experimental procedures and consent form were approved by the Texas A&M Internal Review Board for the ethical treatment of animal and human subjects. Nine undergraduate students (four males and five females) attending Texas A&M University gave their informed consent by signing the approved consent form prior to participating in the experiment. The nine students received class credit for participation and were all self-reported right-handers.

### Protocol

The apparatus consisted of a freely rotating wooden horizontal lever that was affixed at one end to a near frictionless vertical axle (ball-bearing supports) mounted in a table. Attached to the distal end of the lever was a metal rod (3-mm diameter, bent at 45° at roughly half its length) that served as the target pointer with which subjects were instructed to hit the targets. The distance from the lever's axis of rotation to the bent metal target pointer was 42 cm. Near the end of the lever was a wooden handle mounted perpendicular to the bar. The handle's position was adjustable between 31 and 36 cm from the axis of rotation of the lever, allowing for the elbow to be centered over the vertical axle. The positioning of the horizontal lever limited forearm motion to flexion–extension in the horizontal plane such that maximum elbow flexion would place the handle end of the lever near the body midline. Attached to the lower end of the vertical axle was a potentiometer, which monitored the horizontal movement of the lever. The potentiometer signal was sampled at 200 Hz and stored on a computer for later offline analysis. The targets consisted of 5-cm long rectangles with a specific width (W). Three target pairs were formed: (1) big targets, W=7 cm, (2) small targets, W=0.64 cm, and (3) mixed targets with near target W=7 cm (elbow flexion) and far target W=0.64 cm (elbow extension). Target amplitude was fixed in all three conditions at 18.5 cm (25.2° of rotation between target centers) along the arc of the circle defined by the 42 cm lever and pointer assembly. The index of difficulty (ID) for the big target pair was 2.40 and for the small target pair 5.85. The targets were placed on a table that supported the horizontal lever with the targets positioned to ensure that the target pointer was aligned with the target center. Since the targets were aligned to the target pointer there was no blockage of the targets upper-half by the movement of the subject's forearm. Subjects performed ten control trials of the big and small target conditions before performing five practice blocks of ten trials in the mixed target condition. Each trial lasted 10 s with 10 s rest between trials and 3 min rest between target conditions. On the average, subjects generated 6.7 cycles (13.4 movement reversals) of movement in the small target condition, 28 cycles (56 movement reversals) of movement in the big target condition, and 9.6 cycles (19.3 movement reversals) of movement in the mixed target condition. Subjects were instructed to be as accurate as possible but to move as quickly as possible with emphasis placed on accuracy in this experiment (Adam 1992).

### Data analysis

The dependent measures outlined below were computed from those trials with no more than one missed target hit. All trials from the big target condition were available for analysis, with 86% of the trials from the small target and 98% of the trials from the mixed target conditions available for analysis.

*End-effector kinematics.* Individual trial time-series were used to compute movement time (MT), dwell time (DT), proportion of MT accelerating and decelerating during the aimed movement, and
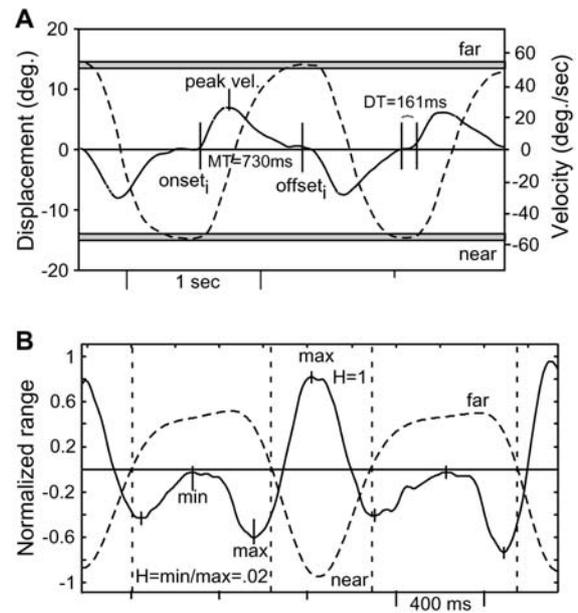


**Fig. 2A,B** Computation of dwell time (*DT*) and movement time (*MT*) values and the harmonicity measure (*H*). **A** DT and MT computation using several cycles of motion for a small target condition trial. **B** Computation of H for a trial from the mixed target condition. The value of H was determined from the minima and maxima in the acceleration trace for every half-cycle of motion as defined by the *vertical dashed lines*. The position trace is the *dashed line* in both plots; the velocity (**A**) and acceleration (**B**) traces are the *solid lines*

variability in end-point position at movement reversal. These measures were computed for every half-cycle of motion between target strikes in a trial with the values averaged as a function of near or far target strike in each of the three target conditions.

Movement onset was determined with reference to the value of peak velocity (positive or negative, depending on movement direction) in each movement segment. From the point of peak velocity, a search backwards was performed to find the first point in the velocity trace that was 5% of the peak velocity value. From this 5% value, if the next seven sampled points had velocities >5% of the peak velocity, then that first sampled point at 5% of the peak velocity was taken to represent movement onset (Fig. 2A). Movement offset was located by searching forward from the peak velocity value to find the last point that was 5% of the peak velocity value before movement reversal (Fig. 2A). Based on the onset and offset points from the velocity trace, movement time is defined as $MT = movement\ offset_i - movement\ onset_i$. Dwell time is a measure of time spent on target when end effector motion is stationary over the target. In this experiment dwell time is defined as $DT = movement\ onset_{i+1} - movement\ offset_i$. Acceleration time was taken as the time from movement onset until peak velocity and deceleration time was taken as the time from peak velocity until movement offset. The acceleration and deceleration times are presented as a proportion of total movement time. The maximum (or minimum) value of displacement that occurred between movement onset and movement offset for each target strike was taken as the point of movement reversal. For each target in a trial, the displacement values were averaged and the standard deviation (SD) of this average was taken as the variability in end-point position at movement reversal for each target in a trial.

To investigate the discrete and continuous nature of the end-effector trajectory as discussed by Guiard (1993), an index of harmonicity (H) was computed based on inflection points in the angular acceleration time-series. To reduce noise in the acceleration signal, the angular displacement time-series was filtered with a

second-order dual-pass Butterworth filter with a cutoff frequency of 10 Hz. A three-point-difference algorithm was used to compute the velocity signal. The velocity signal was smoothed with a mobile three-point average algorithm before computing angular acceleration using a three-point difference algorithm. Time-windows of half-cycle motion in displacement were defined as sections of the displacement time-series between every pair of zero crossings, such that each half-cycle contained a movement reversal. The value of H was computed as the ratio of minimum to maximum acceleration within each window of half-cycle motion (Fig. 2B). Whenever H was <0 (one inflection point positive and one negative), the value of H was set to zero. A value of H=1 represents complete harmonicity or cyclic movement in the displacement trace, whereas a value of H=0 represents the concatenation of discrete segments in the displacement trace. The value of H=0.5 is adopted here as the demarcation point between discrete and cyclical motion (Guiard 1997). For each trial, a mean value of H was computed from the individual half-cycle estimates, and is referred to as the full-cycle H-value. The full-cycle H-value represents the cyclical or discrete nature of motion for a single trial.

Even though the value of H is computed on a half-cycle basis, the H-value presented in prior research has been the mean value computed from the two half-cycle estimates in a target pair (Guiard 1993, 1997). This presentation assumes that the H-values from each half-cycle are approximately equal due to the equal target widths in a target pair. However, in this experiment, the mixed target condition offers the opportunity to examine H as a function of target size within the same trial (mixed targets) instead of just across target conditions (big versus small). For this reason, a half-cycle value of H was computed as a function of target side (near and far) in a manner consistent with the MT, DT and acceleration–deceleration time data.

*Statistical analysis.* Two statistical analyses were performed: (1) on baseline data, and (2) on practice data. The baseline analyses compared data from the big target condition, small target condition, and first block of the mixed target condition. The dependent measures of MT, DT, acceleration–deceleration time, half-cycle H, and end-point variability were analyzed in a 3 target condition (big, small, mixed) × 2 movement direction (near and far) repeated measures analysis of variance (ANOVA). The full-cycle H data averaged across both targets in a trial in the baseline analysis were analyzed in a three-target condition (low, high, mixed) repeated measures ANOVA. Target condition and movement direction means for the baseline data are presented in the section on baseline target condition kinematics. The practice data from the five blocks of the mixed target condition were analyzed in a 5 block × 2 movement direction (near, far) repeated measures ANOVA. The full-cycle H data averaged across both targets in a trial from the practice blocks were analyzed in a five-block repeated measures ANOVA. The results from the practice blocks are presented in the mixed target condition practice section. The significance level for tests of all main effects (Duncan's multiple range test) and interaction effects was set at $p<0.05$.

## Results

### Baseline target conditions: modification of movement kinematics

*Movement time.* On average, MT in the small target condition (744 ms) was significantly longer than MT in the big target condition (178 ms) and mixed target condition (515 ms), with MT in the mixed target condition significantly longer than MT in the big target condition ($F_{(2,16)}=186.9$, $p<0.01$). A significant interaction between target condition and movement direction revealed three noteworthy findings in the MT data

($F_{(2,16)}=24.1$, $p<0.01$). First, tests of the interaction revealed a significant difference in MT between the near and far target in the small target and mixed target conditions (Table 1). Second, the mixed target condition increased MT to the big target. This is supported by significantly longer MTs to the big target (near target) in the mixed target condition compared with MTs to the near target in the big target condition. Third, the mixed target condition shortened MT to the small target. This is supported by significantly shorter MTs to the small target (far target) in the mixed target condition compared with those to the far target in the small target condition.

*Harmonicity: full-cycle H.* Target condition had a significant impact on the dynamics of the end-effector's trajectory (Fig. 3). End-effector motion in the big target condition was cyclical with maximum acceleration occurring over the targets (Hooke portrait, Fig. 3A), and maximum velocity occurring at the midpoint between target strikes (phase plane, Fig. 3A). Overall, 95% of the trials in the big target condition had full-cycle H-values ≥0.98 (Fig. 4A). Motion of the end-effector in the small target condition was discrete with many equilibrium points (acceleration =0, velocity =0) associated with movement reversal (Hooke portrait, Fig. 3C) over the targets and maximum velocity before the midpoint between target strikes (phase plane, Fig. 3C). All of the trials in the small target condition had full-cycle H-values <0.5, with 38% of the trials having full-cycle H-values <0.1 (Fig. 4A). The mixed target condition did not result in two separate discrete movements. This is evident in that maximum acceleration occurred as the pointer moved across the big target (Hooke portrait, Fig. 3B). Although equilibrium points occur with movement reversal over the small target in the mixed target condition, the shape of the acceleration profile is different from that observed for the same target side in the small target condition (compare Fig. 3B and C). In the mixed target condition, 86% of the trials had full-cycle H-values >0.5 (Fig. 4A). Statistical analysis supports the observed differences in the discrete and cyclical nature of the end-effector's motion ($F_{(2,16)}=257.9$, $p<0.01$). Post hoc tests revealed that the full-cycle H-value in the big target condition (H=0.99, SD=0.01) was significantly larger than the full-cycle H-value in the small target condition (H=0.16, SD=0.11) and in the mixed target condition (H=0.53, SD=0.07), with the small and mixed conditions also being significantly different.

*Harmonicity: half-cycle H.* The most important result in the half-cycle H data was a significant target condition × movement direction interaction ($F_{(2,16)}=123.3$, $p<0.01$). This interaction revealed three important findings about the trajectory's dynamics as a function of target condition (Table 1). First, the half-cycle H-values for the big target (near target) in the mixed target condition were significantly different from the half-cycle H-values for the near target in the big target condition. Second, the half-cycle H-values for the small target (far target) in the mixed
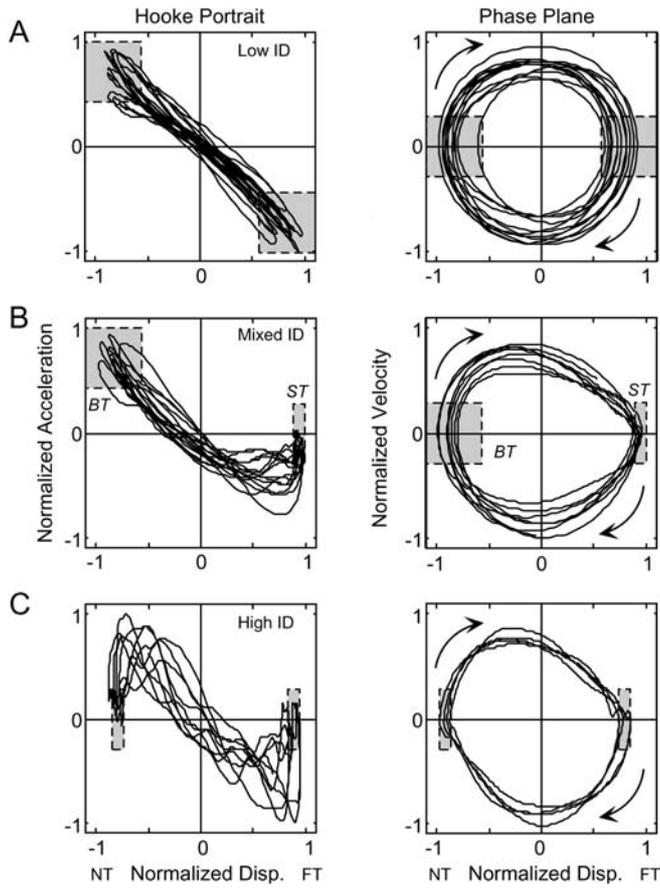
**Fig. 3A–C** End-effector trajectories (normalized) representative of the big (**A**), mixed (**B**) and small (**C**) target conditions from experiment I have been plotted in the form of Hooke portraits (*left column*) and phase planes (*right column*). *FT* far target, *NT* near target, *ST* small target, *BT* big target, *Disp.* displacement. *Shaded rectangles* represent movement reversal over the targets; *arrows* represent the direction of motion along the plots

target condition were not different from the half-cycle H-values for the far target in the small target condition. Third, in the big and small target conditions there was no significant difference in the half-cycle value of H as a function of movement direction (near versus far). A main of effect of target condition revealed the same finding as the full-cycle analysis with regard to H ($F_{(2,16)}=231.6$, $p<0.01$).

*Acceleration and deceleration.* Approximately 49% of the MT consisted of the acceleration phase in the big target condition, with proportionally less MT belonging to the acceleration phase in the small target (42%) and mixed target conditions (43%) ($F_{(2,16)}=110.2$, $p<0.01$). A significant target condition × movement direction interaction revealed three noteworthy findings regarding the acceleration phase of the movement ($F_{(2,16)}=46.4$, $p<0.01$). First, the proportion of MT characterized as the acceleration phase was not significantly different as a function of movement direction (near and far target) in the big and small target conditions (Table 1). This may be seen in the

**Table 1** Movement kinematics (means and standard deviations, SD) as a function of target condition and movement direction for big, small, and mixed target condition—practice blocks 1 and 5 (*B* big target, *S* small target)

| Kinematic parameter | Big target | | | | Small target | | | | Mixed target | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Block 1 | | | | Block 5 | | | |
| | Near | | Far | | Near | | Far | | Near (B) | | Far (S) | | Near (B) | | Far (S) | |
| | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| Movement time (ms) | 178 | 38 | 179 | 37 | 728 | 123 | 761 | 88 | 427 | 49 | 604 | 83 | 369 | 50 | 601 | 100 |
| Acceleration (%) | 49.4 | 11 | 49.2 | 11 | 41.7 | 7 | 41.6 | 10 | 58.7 | 6 | 28.6 | 5 | 59.8 | 7 | 25.1 | 5 |
| Deceleration (%) | 50.6 | 8 | 50.8 | 9 | 58.3 | 12 | 58.4 | 8 | 41.3 | 7 | 71.4 | 10 | 40.2 | 7 | 74.9 | 12 |
| Half-cycle H | 0.99 | 0.01 | 0.99 | 0.01 | 0.16 | 0.10 | 0.20 | 0.15 | 0.85 | 0.10 | 0.22 | 0.10 | 0.85 | 0.10 | 0.41 | 0.15 |
| Dwell time (ms) | 7 | 1.3 | 7 | 1.3 | 147 | 77 | 142 | 78 | 14 | 3 | 144 | 46 | 11 | 2 | 160 | 69 |
| End-point Variability (degrees) | 9.5 | 1.0 | 10.2 | 1.3 | 4.7 | 2.4 | 1.5 | 0.04 | 7.2 | 1.3 | 1.5 | 0.21 | 7.5 | 1.1 | 1.7 | 0.3 |
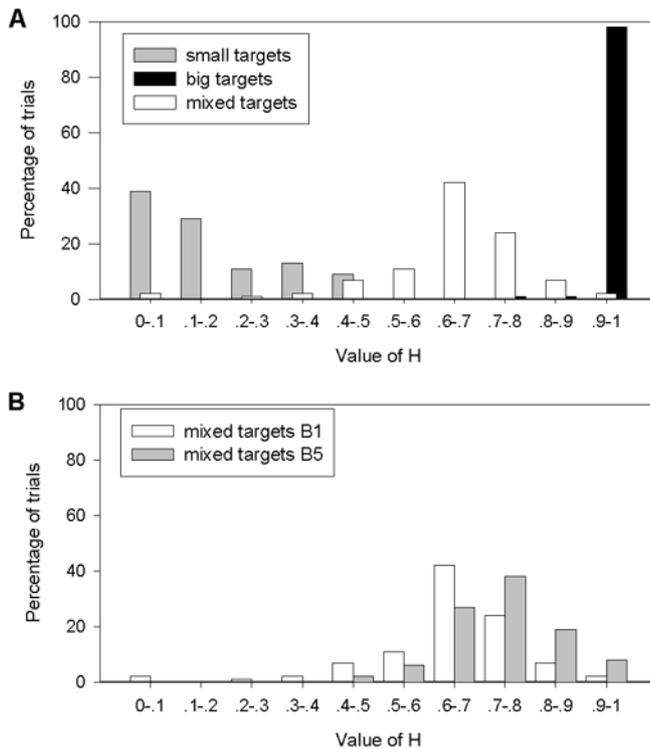
**Fig. 4A,B** Histograms of full-cycle H-values as a function of target condition for experiment I. In both plots, the H-values were separated into 10 bins with each bin having a range of 0.1. **A** Percentage of trials for each H-bin plotted for the big target, small target, and first practice block of the mixed target condition. **B** Percentage of trials for each H-bin plotted for the first (*B1*) and fifth (*B5*) practice blocks of the mixed target condition

similarity of the half cycle segments portrayed in the phase plane plots shown in Fig. 3A, C. Second, the proportion of MT belonging to the acceleration phase when moving to the big target (near target) in the mixed target condition was significantly larger than the acceleration phase to the near target in the big target condition. Third, the proportion of MT belonging to the acceleration phase to the small target (far target) in the mixed target condition was significantly smaller than the acceleration phase to the far target in the small target condition.

Approximately 51% of the MT was characterized as the deceleration phase in the big target condition, whereas in the small (58%) and mixed target (56%) conditions a greater proportion of MT was classified as the deceleration phase ($F_{(2,16)}=165.5$, $p<0.01$). A significant target condition × movement direction interaction was found in the deceleration data ($F_{(2,16)}=64.4$, $p<0.01$). Tests of the interaction found that the proportion of MT characterized as the deceleration phase was not significantly different as a function of movement direction (near and far) in the big target and small target conditions (Table 1). In the mixed target condition, a significantly larger proportion of MT was characterized as part of the deceleration phase when approaching the small target compared with approach to the large target. The proportion of MT belonging to the deceleration phase when moving to the big target (near target) in the mixed condition was smaller than the deceleration phase when moving to the near target in the big target condition. The proportion of MT belonging to the deceleration phase when moving to the small target (far target) in the mixed target condition was significantly larger than the time spent decelerating to the far target in the small target condition.

*Dwell time*. Longer dwell times occurred in the small target condition (144 ms) than in the big target condition (7 ms), with the time on target in the mixed target condition (79 ms) being significantly different from the big and small target conditions ($F_{(2,16)}=29.1$, $p<0.01$). A significant target condition × movement direction interaction was found in the dwell time data ($F_{(2,16)}=42.3$, $p<0.01$). The interaction was the result of longer dwells on the small target than on the large target in the mixed target condition, with no significant difference between the same size targets in the mixed target condition compared with the small and big target conditions (Table 1).

*End-point variability*. Variability in end-point position associated with movement reversal in the small target condition was smaller than in the big target and mixed target conditions ($F_{(2,16)}=84.8$, $p<0.01$). A significant target condition × movement direction interaction was found in the end-point variability data ($F_{(2,16)}=34.2$, $p<0.01$). In the mixed target condition, end-point variability over the near big target was reduced significantly compared with that for the near target in the big target condition, whereas end-variability was the same for the small far target in the mixed and small target conditions. In the mixed target condition, end-point variability was larger over the big target than over the small target (Table 1).

*Mixed target condition: extended practice*. Extended practice in the mixed target condition lead to significant changes in the acceleration phase data ($F_{(4,32)}=3.5$, $p<0.01$) and in the full-cycle measure of H ($F_{(4,32)}=3.7$, $p<0.05$). A significant decrease in the proportion of the MT characterized as the acceleration phase occurred from practice blocks 1 (44%) and 2 (44%) to practice block 5 (42%). In the full-cycle H data, a significant increase in H occurred from practice block 1 (H=0.53, SD=0.07) to practice block 5 (H=0.63, SD=0.06), with 98% of the trials in practice block 5 having mean H-values >0.5 (Fig. 4B). A significant practice block × target condition interaction was found in the half-cycle H practice data ($F_{(4,32)}=4.7$, $p<0.01$). Post hoc tests found a significant increase in the half-cycle H-values from practice block 1 to practice block 5 when moving to the small target in the mixed target condition, with no significant change in the half-cycle H-values when moving to the large target in the mixed target condition (Table 1).

Discussion

The results from experiment 1 provide evidence that discrete and cyclical motion might be represented as independent basic units of action that are selected based on task constraints. The big target condition consisted of cyclical motion and the small target condition consisted of discrete motions sequenced together. In the mixed target condition, end-effector motion contained features of both discrete and cyclical motion that were functionally linked (hypothesis 3). The first piece of evidence supporting this conclusion comes from the full-cycle and half-cycle harmonicity data. In practice block 1 of the mixed target condition, the full-cycle H mean was 0.53, a value on the demarcation point between discrete and cyclical motion as defined by Guiard (1997). The means of half-cycle H from the first practice block provide corroborating evidence with a half-cycle mean H =0.85 when moving to the big target and H=0.22 when moving to the small target. The second piece of supporting evidence comes from the dwell time data. The dwell times did not change for either the small or large target in the mixed target condition. This is suggestive of equilibrium points associated with movement reversal over the small target and maximum acceleration occurring over the large target in the mixed condition. Another interesting finding was that the mixed target condition increased the proportion of MT belonging to the acceleration phase when moving to the big target, while decreasing the proportion of MT belonging to the acceleration phase when moving to the small target. These changes in the acceleration profile suggest that the motor system in the mixed condition exploited the big target to shorten MT to the small target without increasing the number of target misses or increasing variability in end-point position. The proportionally longer deceleration time to the small target in the mixed condition represents more time to process visual feedback, which is essential since MT is faster by 200 ms relative to the small target condition. The change in the acceleration profile did come with a cost in that MT lengthened to the big target in the mixed target condition. However, the longer MTs were associated with a decrease in end-point variability over the big target in the mixed condition. The increase in the full-cycle value of H with practice suggests that the system may be biased towards more cyclical motion in this task. The significant increase in the half-cycle H value with practice when moving to the small target also supports a strong tendency towards cyclical motion.

# Experiment II

## Materials and methods

Experiment II was designed to extend the findings from the 1-degree-of-freedom (1D) motion task to a 2-degrees-of-freedom (2D) motion task. There are three important issues based on the results from experiment I that were examined in experiment II: (1) Will the big target and small target conditions be consistently cyclical and discrete, respectively? (2) Will the mixed target condition contain both cyclical and discrete units that have been functionally linked? (3) Will extended practice lead to similar changes in the value of H and in the acceleration phase data?

### Subjects

The experimental procedures and consent form were approved by the Texas A&M Internal Review Board for the ethical treatment of animal and human subjects. Six undergraduate students (two males and four females) attending Texas A&M University gave their informed consent by signing the approved consent form prior to participating in the experiment. The six students received class credit for participation and were all self-reported right-handers.

### Protocol

An Optotrak 3020 camera system (Northern Digital, Waterloo Canada) was used to record the three-dimensional motion of two infrared light-emitting diodes (IREDs) placed on a pencil-sized stylus that was held by the subject. The two IREDs were separated by 11.5 cm with the lower IRED mounted 4 mm from the bottom of the stylus. The IREDs were sampled at 200 Hz and stored offline on a computer for later analysis. The IRED data were filtered with a second-order Butterworth filter (cutoff frequency 10 Hz) prior to analysis. Movement in the $y$-direction represents vertical height above the targets and movement in the $x$-direction represents the horizontal distance between the targets.

The targets were of the same size as the targets used in experiment I, small (0.64 cm) and big (7 cm), with movement amplitude fixed at 18.5 cm on target center. In the mixed target condition, the left side target was the big target (ID=2.4) and the right side target was the small target (ID=5.85). Thus, the ID values were constant across the experiments in all three conditions. Each target pair was drawn on a piece of paper and placed under a piece of plexi-glass that was secured to a table. Subjects sat in a height-adjustable chair with the targets positioned approximately waist high. Subjects performed ten practice trials of the big and small target conditions before performing five blocks of ten trials in the mixed target condition. Each trial lasted 10 s with 10 s rest between trials and 3 min rest between target conditions. On average, subjects produced 8.9 cycles of movement (17.9 target strikes) in the small target condition, 17.2 cycles of movement (34.4 target strikes) in the big target condition, and 11 cycles of movement in (22.1 target strikes) in the mixed target condition. Subjects were instructed to move as quickly as possible between the targets with an emphasis placed on accuracy (Adam 1992).

### Data analysis

The dependent measures described below were computed from those trials with no more than one missed target hit in the entire trial. All of the trials in the big target condition were available for analysis, with 93% of the trials in the small target condition and 98% of the trials in the mixed target condition available for analysis.

*End-effector kinematics.* Individual trial time-series were used to compute MT, DT in $y$-motion, a movement adjustment time in $x$-motion, acceleration and deceleration phases of MT, and end-point variability at movement reversal. These measures were computed for every target strike in a trial with values averaged as a function of left or right side in the three target conditions.

Movement time was computed from the $y$-velocity time-series based on the time of target strike and target liftoff. To determine target strike, negative peak $y$-velocity within a movement segment was located, and a search forward from negative peak $y$-velocity was performed until the first point that was 5% of the peak value was located. From this 5% value, if the next seven points had
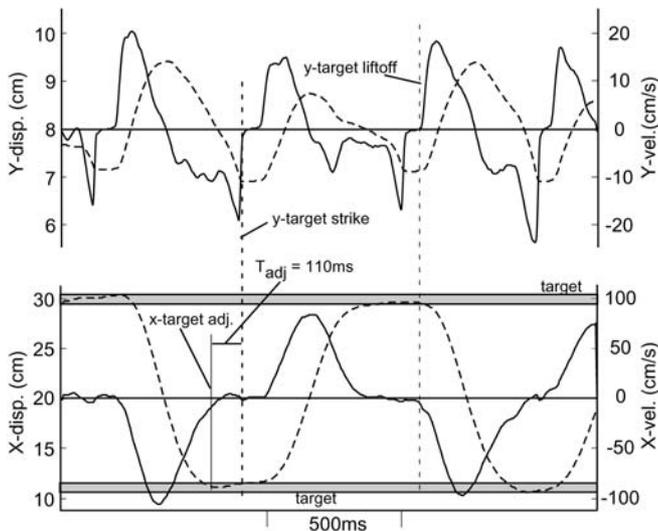
**Fig. 5** Computation of movement dwell time in the *y*-direction (*top*) and adjustment time in the *x*-direction (*bottom*) is shown for a representative trial from the small target condition. The *dashed line* time-series are end-effector displacements (*disp.*)and the *solid line* time-series are end-effector velocities (*vel.*) for both directions of motion. The relevant events associated with *y*-target strike and *y*-target liftoff (*dashed vertical lines*) are shown in the top plot, and the relevant events associated with *x* adjustment (*solid vertical lines*) are shown in the bottom plot. See Data analysis section for details on computing dwell time in *y* and adjustment phase in the *x*-direction ($T_{adj}$). *Shaded regions* in the bottom plot represent target location

velocities <5% of the negative peak velocity, or the point of target liftoff of the next segment was surpassed, then the first sampled point at 5% of the negative peak velocity was taken to represent target strike (Fig. 5 *top*). To determine target liftoff, a backward search was performed from the point of positive peak *y*-velocity in a segment until the first point that was 5% of positive peak *y*-velocity was located. If the next seven points were >5% of the positive peak velocity, then that first point at 5% of the positive peak velocity was taken as the point of target liftoff (Fig. 5 *top*). Based on the *y*-velocity values, movement time between targets was defined as $MT_y = |y\text{-}target\ liftoff_j - y\text{-}target\ strike_j|$. The temporal length of the acceleration phase was taken as the time from *y*-target liftoff to the time of peak velocity in the *x*-direction, and the temporal length of the deceleration phase was taken as the time from peak velocity in the *x*-direction to the time of *y*-target strike. The acceleration and deceleration time data are reported as proportions of total MT. The position of the stylus in the *x*-direction associated with the point of target strike in the *y*-direction was taken as the point of movement reversal. For each target in a pair, the movement reversal points in *x* were averaged and the SD of this average was taken as a measure of end-point variability at movement reversal.

The actual time spent on target, referred to as dwell time in this task, was based on the events of *y*-target strike and *y*-target liftoff, $DT_y = |y\text{-}target\ strike_j - y\text{-}target\ liftoff_{j+1}|$. Detailed examination of motion in the *x*-direction revealed significant adjustments in *x*-motion prior to target strike in *y*, especially in the small target and mixed target conditions. To analysis the observed adjustments in *x*-motion, the *x*-axis time series were analyzed in terms of an adjustment phase associated with *y*-target strike. The start of the adjustment phase in *x* (*x*-target adj.) was defined as the first point when *x*-velocity was at 5% of the peak *x*-velocity (positive or negative depending on the direction of motion) prior to target strike during the deceleration phase of the movement (Fig. 5 *bottom*). The adjustment phase in the *x*-direction was defined as $T_{adj} = x$-

*target adj* $_j - y$-*target strike* $_j$. A negative value of $T_{adj}$ indicates that motion in the *x*-direction is slowing at a different rate than motion in the *y*-direction just prior to target strike in *y*.

Full-cycle and half-cycle values of H for motion in the *x*-direction were computed using the same algorithm outlined in the Data analysis section of Experiment I.

*Statistical analysis.* The data from this experiment were also analyzed based on baseline and practice conditions. The data were analyzed in repeated measures ANOVAs as outlined for experiment I. The baseline data is presented first, followed by the presentation of the practice data from the five blocks of the mixed target condition.

## Results

### Baseline target conditions: modification of movement kinematics

*Movement time in the y-direction.* Movement time varied significantly as a function of target condition with the shortest MTs associated with the big target condition (290 ms) and the longest MTs associated with the small target condition (556 ms), and with MTs for the mixed target condition falling between the small and big target conditions (453 ms) ($F_{(2,10)}=81.8$, $p<0.01$). The three most important results found in the MT data were revealed in a significant interaction between target condition and movement direction ($F_{(2,10)}=74.6$, $p<0.01$). First, movement direction (left or right) did not significantly affect MT in the small and large target condition, but did in the mixed target condition with MTs shorter to the big target than to the small target (Table 2). Second, MT was significantly shorter to the small target (right target) in the mixed target condition than to the right target in the small target condition. Third, MT was significantly longer to the big target (left target) in the mixed target condition than to the left target in the big target condition.

*Harmonicity: full-cycle H.* Target condition had a significant impact on the dynamics of the end-effector trajectory in the *x*-direction. In general, movement in the *x*-direction in the big target condition was predominantly cyclical and characterized by maximum acceleration occurring at movement reversal (Hooke portrait, Fig. 6A), and maximum velocity occurring midway between the targets (phase plane, Fig. 6A). Overall, 95% of the trials in the big target condition had full-cycle H-values >0.5, with 65% having full-cycle H-values >0.9 (Fig. 7A). End-effector motion in the *x*-direction in the small target condition was predominantly discrete with equilibrium points (acceleration =0, velocity =0) associated with target strike (Fig. 6C) in many of the trials. In the small target condition, 93% of the trials had full-cycle H-values <0.5, with 58% having full-cycle H-values approaching zero (<0.1) (Fig. 7A). End-effector motion in the mixed target condition contained features from both the big and small target tasks. This is seen in the maximum accelerations at the reversal point associated with the big target strike and equilibrium points associ-

**Table 2** Movement kinematics (means and standard deviations, SD) as a function of target condition and movement direction: big, small and mixed target conditions—practice blocks 1 and 5. (*LT* left target, *RT* right target, *B* big target, *S* small target)

| Kinematic parameter | Big target | | | | Small target | | | | Mixed target | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | | | | | | | | | Block 1 | | | | Block 5 | | | |
| | LT | | RT | | LT | | RT | | LT (B) | | RT (S) | | LT (B) | | RT (S) | |
| | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| Movement time (ms) | 300 | 59 | 281 | 61 | 551 | 94 | 56 | 101 | 401 | 80 | 506 | 66 | 383 | 85 | 465 | 68 |
| Acceleration (%) | 49.0 | 6 | 53.4 | 9 | 37.5 | 3 | 39.6 | 4 | 49.4 | 4 | 33.4 | 5 | 49.9 | 5 | 35.5 | 6 |
| Deceleration (%) | 51.0 | 14 | 46.6 | 13 | 62.5 | 18 | 60.4 | 17 | 50.6 | 16 | 66.6 | 8 | 50.1 | 18 | 64.5 | 11 |
| Half-cycle H | 0.91 | 0.14 | 0.91 | 0.07 | 0.19 | 0.23 | 0.13 | 0.20 | 0.74 | 0.21 | 0.07 | 0.10 | 0.85 | 0.19 | 0.14 | 0.12 |
| Dwell time (ms) | 25 | 9 | 32 | 12 | 64 | 33 | 81 | 43 | 35 | 12 | 76 | 46 | 35 | 8 | 65 | 41 |
| Dwell adjust. (ms) | 2 | 5 | 14 | 10 | -64 | 99 | -94 | 94 | 2 | 7 | -93 | 42 | 2 | 5 | -44 | 33 |
| End-point Variability (mm) | 5.7 | 1.4 | 5.2 | 0.7 | 1.6 | 0.4 | 0.22 | 0.5 | 4.9 | 1.3 | 2.3 | 0.4 | 4.8 | 1.7 | 1.8 | 0.6 |
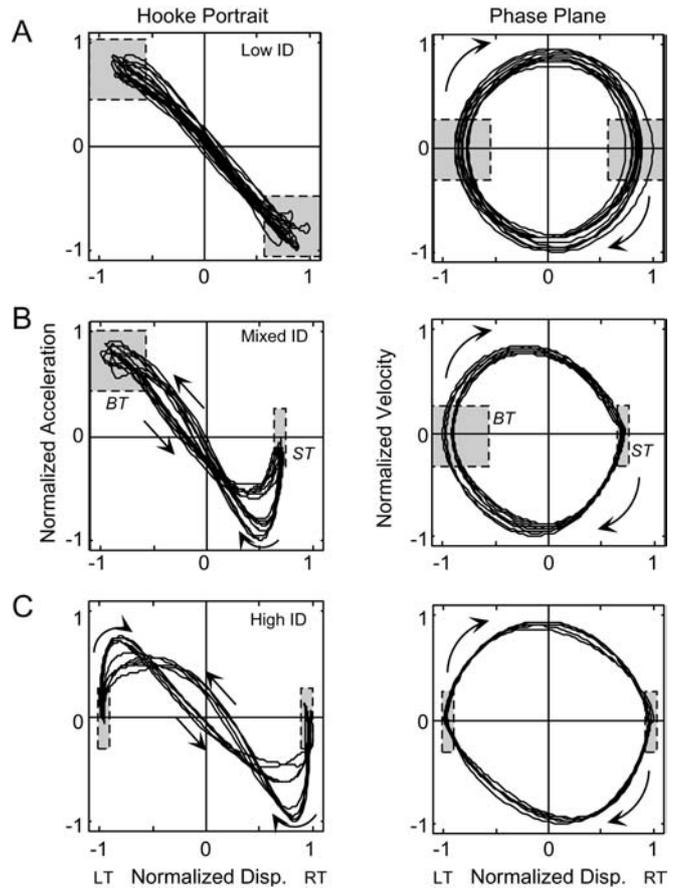


**Fig. 6A–C** End-effector trajectories (normalized) representative of the big (**A**), mixed (**B**) and small (**C**) target conditions from experiment II plotted in the form of Hooke portraits (*left panels*) and phase planes (*right panels*). *LT* left target, *RT* right target, *ST* small target, *BT* big target, *Disp.* displacement. *Shaded rectangles* represent movement reversal over the target; *arrows* represent the direction of motion along the plots

ated with the small target strike. While containing features of the other two tasks, the end-effector's trajectory in the mixed condition was unique in terms of decelerating into the target and accelerating away from the target (Fig. 6B). In the mixed target condition, 44% of the trials had full-cycle H-values >0.5, which would be considered cyclical, while 56% of the trials had full-cycle H-values <0.5, and these would be considered discrete (Fig. 7A). Statistically, the target conditions were characterized by different full-cycle H-values ($F_{(2,10)}$=81.5, $p$<0.01). Post hoc tests found the largest full-cycle H-values in the big target condition (H=0.88, SD=0.14), the smallest full-cycle H-values in the small target condition (H=0.14, SD=0.2), with the full-cycle H-values for the mixed condition (H=0.43, SD=0.13) being different from the small and big condition.

*Harmonicity: half-cycle H.* The most important result in the half-cycle H data was a significant target condition × movement direction interaction ($F_{(2,10)}$=74.7, $p$<0.01). This interaction revealed two important findings about the
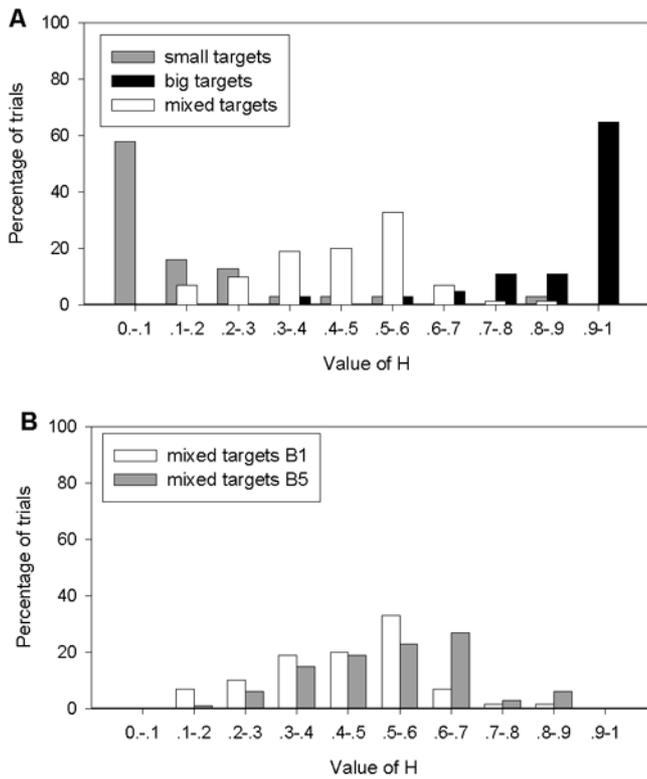
**Fig. 7A,B** Histograms of full-cycle H-values as a function of target condition for experiment II. In both plots, the H-values were separated into 10 bins with each bin having a range of 0.1. **A** Percentage of trials for each H-bin for the big target, small target, and first practice block of the mixed target condition. **B** Percentage of trials for each H-bin has been plotted for the first (*B1*) and fifth (*B5*) practice blocks of the mixed target condition

trajectory's dynamics as a function of target condition (Table 1). First, the half-cycle value of H in the mixed target condition was significantly larger when moving to the big target than to the small target. Second, the half-cycle H-values when moving to the big target (left target) and the small target (right target) in the mixed target condition were not significantly different from the half-cycle value of H when moving to the left target and right target in the big and small target conditions, respectively.

*Acceleration and deceleration*. Approximately 51% of the MT was characterized as the acceleration phase in the big target condition, with a much smaller proportion of MT in the acceleration phase in the small target condition (38%) and mixed target condition (41%) ($F_{(2,10)}$=25.8, $p$<0.01). A significant target condition × movement direction interaction revealed three important findings with regard to the acceleration phase ($F_{(2,10)}$=25.5, $p$<0.01). First, movement direction (right or left target) did not significantly affect the proportion of MT belonging to the acceleration phase in the small and big target conditions (Table 2). This may be seen in the similarity of the half-cycle segments portrayed in the phase plane plots shown in Fig. 6A, C. Second, a greater proportion of MT was characterized as the acceleration phase when moving to

the big target compared to the small target in the mixed target condition. Third, a smaller proportion of MT was characterized as the acceleration phase when moving to the small target (right target) in the mixed target condition than to the right target in the small target condition, with no difference in the proportion of MT belonging to the acceleration phase when moving to the left side big target in the big and mixed target conditions.

Approximately 49% of MT was characterized as the deceleration phase in the big target condition, with much larger proportions of MT belonging to the deceleration phase in the small (61%) and mixed (58%) target conditions ($F_{(2,10)}$=39.5, $p$<0.01). The interaction between target condition and movement direction was significant for the deceleration phase data ($F_{(2,10)}$=110.1, $p$<0.01). Tests of the interaction found a greater proportion of MT belonging to the deceleration phase when moving to the small target (right target) in the mixed target condition than when moving to the right target in the small target condition. No significant differences were found between the big target across the mixed and big target conditions (Table 2).

*Dwell time in the y-direction*. Overall, dwell time was longest in the small target condition (72 ms) and shortest in the big target condition (29 ms), with the time spent on target in the mixed target condition (56 ms) being significantly different from the big and small target conditions ($F_{(2,10)}$=7.84, $p$<0.01). Significantly more time was spent on the right side target than the left side target across the three target conditions ($F_{(1,5)}$=8.8, $p$<0.05) (Table 2). This may result from the right side target in the mixed condition being the small target. However, without a significant interaction between target condition and movement direction this is not definitive.

*Adjustment time in the x-direction*. The length of the adjustment phase ($T_{adj}$) in the x-direction varied significantly between the small ($T_{adj}$=−79 ms) and big ($T_{adj}$=8 ms) target conditions, with the mixed target ($T_{adj}$=−91 ms) condition being significantly different from both the small and big target conditions ($F_{(2,10)}$=4.3, $p$<0.05). A significant target condition × movement direction interaction revealed three important findings in the $T_{adj}$ data ($F_{(2,10)}$=18.0, $p$<0.01). First, $T_{adj}$ in the big target and the small target condition was not different as a function of movement direction (left and right target) within either condition (Table 2). Second, there was no difference in $T_{adj}$ between the small targets in the small and mixed target conditions, and no difference between $T_{adj}$ in the big targets in the big and mixed target conditions. Third, $T_{adj}$ was significantly longer when moving to either target in the small target condition compared to the big target conditions.

*End-point variability*. The point of movement reversal in x was least variable in the small target condition and most variable in the big target condition, with the mixed target condition being significantly different from both the small

**Table 3** Full-cycle and half-cycle values of H for all practice trials in the mixed target condition

| | Full-cycle H | | Big target half-cycle H | | Small half-cycle target H | |
|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD |
| Subjects 1, 2, and 6 | 0.52 | 0.41 | 0.90 | 0.09 | 0.15 | 0.15 |
| Subjects 3, 4, and 7 | 0.31 | 0.31 | 0.58 | 0.12 | 0.03 | 0.05 |

and big target conditions ($F_{(2,10)}=83.0$, $p<0.01$) (Table 1). The interaction between target condition and movement direction was also significant in the end-point variability data ($F_{(2,10)}=12.0$, $p<0.01$). Tests of the interaction revealed that end-point variability in the mixed target condition was significantly smaller for the small target than for the big target. Also, end-point variability was larger on the left target (big target) in the big target condition than on the left target (big target) in the mixed target condition (Table 2).

*Mixed target condition: extended practice*

With practice, the full-cycle H-values increased significantly from practice block 1 (H=0.43, SD=0.13) to practice block 5 (H=0.53, SD=0.14), as did the half-cycle H-values ($F_{(4,24)}$-values >2.8, $p$-values <0.05; Table 2). Even with this overall shift in the full-cycle H-values to above 0.5 with practice, 41% of the trials still had full-cycle H-values <0.5 in practice block 5 (Fig. 7B). Extended practice with the mixed target condition also produced a significant block effect in the measure of $T_{adj}$ in the x-direction ($F_{(4,24)}=3.2$, $p<0.05$), with the value of $T_{adj}$ decreasing significantly from practice block 1 (–91 ms) to practice block 5 (–42 ms). A significant interaction between practice block and movement direction was found in the $T_{adj}$ data ($F_{(4,20)}=3.3$, $p<0.05$). Tests of the interaction revealed two important findings. First, $T_{adj}$ was always large and negative when moving to the small target and near zero when moving to the large target. Second, $T_{adj}$ decreased significantly from practice block 1 to practice block 5 when moving to the small target, and remained constant across blocks when moving to the big target (Table 2).

Discussion

The harmonicity results revealed that end-effector motion was cyclical when tapping between the big targets and discrete when tapping between the small targets. In the mixed target condition, the data revealed a near-equal split in the number of trials classified as either discrete or cyclical. Interestingly, three subjects across the five practice blocks had full-cycle H-values on average <0.5, which supports the idea of discrete motion units, whereas the other three subjects had full-cycle H-values >0.5, which supports the idea of cyclical motion units. However, the half-cycle H-values reveal that the solution to the mixed target condition consisted of functionally linking discrete and cyclical units. For example, the

subjects with full-cycle H-values <0.5 had half-cycle H-values close to 0.5 when moving to the big target and near zero when moving to the small target (Table 3). The other three subjects with full-cycle H-values >0.5 had half-cycle H-values close to 1 when moving to the big target and around 0.15 when moving to the small target. The mixed target condition in the 2D task did not alter the equal proportion of MT associated with the acceleration and deceleration phases when moving to the big target as seen in the 1D task. However, the increase in the proportion of MT characterized as the deceleration phase to the small target in the mixed condition was consistent with the 1D task. The acceleration–deceleration data and the MT data suggest that the motor system exploited the low ID of the big target to shorten MT to the small target while ensuring a high target strike frequency and low end-point variability in the 2D task. The positive value of $T_{adj}$ in the big target condition indicates movement stoppage in x was simultaneous with target strike in the y-direction. The negative value of $T_{adj}$ in the small target condition reflects a significant amount of movement slowing in x before target strike in the y-direction. Extended practice led to significantly shorter $T_{adj}$ times in x with a small increase in the full-cycle and half-cycle H-values from practice block 1 to block 5. The decrease in $T_{adj}$ suggests that practice led to an improvement in the estimate of movement amplitude, while the increase in H is suggestive of improvement in terms of the cyclical features of the task.

## General discussion

The two experiments reported examined the influence of mixed target pairing on the end-effector's dynamics in a rhythmical aiming task. Data from both experiments demonstrated that the central nervous system produced a unique solution for the mixed target condition that contained both discrete and cyclical motion characteristics. The uniqueness of the solution was found in the MT data, acceleration–deceleration data, and harmonicity data. Moreover, practice produced a change in harmonicity in both experiments, suggesting that the practice led to improvements that were biased towards cyclical motion. The above findings are discussed in reference to the issue of the basic units of action, the role of vision in error evaluation in repetitive aiming, and the dissipation of mechanical energy with movement reversals. As a final point, important issues that our results raise with respect to modeling repetitive aimed movements are discussed.

## The basic units of action: discrete and cyclical motion units

The harmonicity results and the acceleration–deceleration times clearly support the idea that cyclical motion in the form of a limit-cycle oscillator is the optimal task solution in the big target condition. Over 96% of the trials from both experiments had full-cycle H-values >0.5, with 84% of the trials having full-cycle H-values >0.9 in the big target condition. Approximately equal time was spent accelerating and decelerating with maximum acceleration typically occurring with movement reversal in the big target condition (Figs. 3A, 6A). Both the harmonicity and acceleration–deceleration results are consistent with other work showing that cyclical motion in the form of a limit-cycle oscillator acts as a basic unit of action in a Fitts-type task (Guiard 1993, 1997; Mottet and Bootsma 1999). The harmonicity results and dwell time results support the idea of a discrete unit of action in the form of a fixed-point attractor as the optimal solution in the small target condition. Over 97% of the trials had full-cycle H-values <0.5, with 49% of the trials being consistent with discrete motion (H<0.1) in the small target condition (Guiard 1997, 1993). Moreover, longer dwell times on the small target are consistent with the observation of equilibrium points (acceleration =0, velocity =0) associated with movement reversal (Figs. 3C, 6C).

Evidence for discrete and cyclical units of action in the mixed target condition is found in the same data that supports the independence of discrete and cyclical units of action in the small and big target conditions, respectively. Across both experiments, 70% of the trials were characterized with full-cycle H-values >0.5, indicating cyclical motion, whereas 30% of the trials can be characterized as discrete motion with full-cycle H-values <0.5. However, a more detailed examination of the end-effector's trajectory shows that the solution that emerged consisted of both discrete and cyclical characteristics. For example, half-cycle H-values show that motion towards the big target was cyclical, whereas motion towards the small target was discrete. This is seen clearly in the Hooke portraits and phase planes that show the dynamics of the end-effector in both tasks were unique in the mixed target condition, but also similar. The similarity is in the form of equilibrium points occurring over the small target (discrete motion) and maximum acceleration occurring over the large target (cyclical motion) (Figs. 3B and 6B). Similarity also emerges in the dwell times that did not change for either target size in the mixed target condition: longer over the small target (discrete) and shorter over the small target (cyclical). Uniqueness comes in the form of changes associated with target departure (acceleration) and target approach (deceleration). In the small target condition, a greater proportion of MT was given to decelerating towards a target (1D task 58%, 2D task 61%). The mixed target condition increased the total proportion of MT belonging to the deceleration phase when moving to the small target (1D task 71%, 2D task - 67%). In the 1D task, a similar change was associated with the big target when placed in the mixed target condition. An approximately equal amount of time was spent accelerating (49.4%) and decelerating (50.6%) in the 1D task big target condition, whereas in the mixed target condition the acceleration phase consisted of 60% of the MT. Although acceleration–deceleration proportional times remained equal in the 2D task in the mixed target condition when moving to the big target, the longer MTs reflect a change in the motor output linked to the small target.

The above changes in the trajectory kinematics support the idea of functionally linked discrete and cyclical units of action as the optimal solution for the mixed target task. What defines the basic unit(s) of action that the nervous system builds upon to produce difficult multi-degree of freedom movements? Many hypotheses on the basic unit of action have been put forth, ranging from single motor units to synergistic muscle groups to abstract rules based motor programs. For example, using a mixed target condition in a bimanual coordination task requiring single discrete motions of both hands, Kelso and colleagues demonstrated that the hand moving to a low ID target slowed significantly to move in time with the hand moving to a high ID target. The simultaneous movement of the hands was taken as evidence that the nervous system controlled the bimanual action by functionally linking the two arms to form a coordinative structure or basic unit of action (Kelso et al. 1979a, 1979b). Recently, Schmidt and colleagues stated that the generalized motor program (GMP) can be thought of as a unit of action, i.e. "... a piece of behavior that can be utilized repeatedly in various actions, producing essentially the same movement ... each time." (p 332 of Schmidt et al. 1998). The defining features of a unit from the GMP perspective are invariant relative time and relative force structure that can be scaled across any action in which the unit appears. The hypothesis we propose is in line with recent work by Sternad and colleagues that views basic units of actions in terms of cyclical or discrete motion characterized by limit-cycle and fixed-point dynamics, respectively (Sternad et al. 2000). The rationale is that the limbs in many rhythmic tasks have been modeled as nonlinear limit-cycle oscillators (Haken et al. 1986; Kay et al. 1987; de Guzman et al. 1997), whereas discrete limb movements have been shown to be consistent with equilibrium point dynamics (Feldman 1986; Abend et al. 1982; Bizzi et al. 1992). The hypothesis stated above is consistent with the idea of coordinative structures as proposed by Kelso et al (1979a, 1979b). Movement of the two hands in the bimanual mixed target task may be controlled in two ways: temporally linking two sets of equilibrium-point dynamics, one for each limb, or parameterizing a single equilibrium-point dynamics that controls both limbs. The hypothesis of fixed-point and limit-cycle dynamics, while not consistent with the concept of GMP as proposed by Schmidt et al. (1998), does provide an interesting twist to the concept of the GMP. In regard to GMPs, discrete and cyclical units of actions might be viewed as the most basic GMPs such that more complex actions (or pro-

grams) result from the parameterization of fixed-point and limit-cycle dynamics or a functionally linked combination of the two types of attractors. The concept of parameterizing a GMP in terms of attractor dynamics has recently been discussed in relation to bimanual coordination (Amazeen 2002). While our results do not solve the unit of action debate, they are consistent with other current research and provide a basis upon which the ideas of coordinative dynamics and GMPs can be addressed.

## Movement planning and visual feedback

Adam and Paas (1996) hypothesized that longer dwell times would be associated with the big target in a mixed target condition because the accuracy constraints of the smaller target would require longer programming times. What emerged was no change in dwell times for either target in the mixed condition. This was interpreted as evidence that the longer dwell times on the small target are associated with visual evaluation of target strike (Adam and Paas 1996). This finding is consistent with the dwell time results from both the 1D and 2D experiments presented. However, Adam and Paas (1996) did not investigate the change in the end-effector's motion regarding acceleration and deceleration. The MT and acceleration–deceleration data suggest that the dwell time results in the mixed condition reflect the importance of visual information in the planning and feedback correction processes necessary to functionally link discrete and cyclical units.

Two primary findings support the hypothesis that longer dwell times on the small target in the mixed condition are most probably linked to planning the next movement sequence, instead of the visual evaluation of target strike. First, MT to the small target in the mixed condition was shorter than MT to either small target in the small target condition in both experiments. To ensure accuracy with increased MTs, the motor system increased the proportion of time decelerating the movement to provide adequate time for visually guided corrections of the end-effector's path. This interpretation is consistent with recent work that has shown that time after peak velocity is very important for making online corrections to a planned aiming movement (Proteau and Masson 1997). The importance of vision of the hand during flight compared to vision of the hand only on target has recently been demonstrated in a reciprocal aiming task. Vision of the hand only during target strike produced longer MTs, lower peak velocities, more errors (especially as ID increases), and longer dwell times, compared to those for vision of the hand during flight (Cullen et al. 2001). Thus, the consistent dwell times on the small target in the small and mixed target conditions reflect the equilibrium aspects of the discrete unit when moving to the small target. Second, the adjustment dwell time data ($T_{adj}$) from the 2D task demonstrates that subjects adjust their movements in the horizontal direction just before target strike when moving to the small target but not to the large

target. Moreover, the $y$ dwell times associated with the small target in the 2D mixed target condition (75 ms) are below the lower cutoff estimate of 100 ms for visual feedback processing (Smith and Bowen 1980; Zelaznik et al. 1983; Lee et al. 1983). The above results demonstrate the importance of visual feedback processing in correcting an aimed response, and are consistent with an emerging body of work demonstrating the importance of continual visual monitoring of aiming movements before target strike (Proteau and Masson 1997; Heath et al. 1998; Ricker et al. 1999; Cullen et al. 2001; Elliott et al. 2001).

## Movement braking and dissipation of mechanical energy

The longer dwell times on the small target, regardless of the target condition or the task (1D versus 2D), suggest that dwell time may reflect predominately biomechanical factors associated with end-effector reversal (Nelson 1983; Rosenbaum 1991; Guiard 1993). For example, both Guiard (1993, 1997) and Adam and Paas (1996) propose that in repetitive aiming tasks cyclical motion functions as a mechanical energy-saving device. This results from the fact that muscles are spring-like bodies that can convert kinetic energy into potential energy and vice versa. In other words, the more cyclical the motion the less energy dissipated at movement reversal points. Thus, short dwell times represent the condition in which a significant amount of energy may be stored in an elastic form before movement reversal over a target and used to initiate motion back to the other target. Based on the dwell time measures, mixed target condition did not alter the mechanical energy dissipation associated with the individual targets.

As argued by Guiard (1993), another measure of energy loss is the degree to which an end-effector's trajectory approximates simple harmonic motion. Based on the H-values reported, minimum energy dissipation occurred in the big target conditions, and maximum loss of stored mechanical energy occurred in the small target conditions. In the mixed target condition, full-cycle H-values were on average 0.59 in the 1D task and 0.49 in the 2D task. Both values are on the border of the discrete versus cyclical demarcation point of H=0.5 (Guiard 1997). Although treated as a measure of the harmonic nature of the end-effector's motion over an entire trial, the computation of H is derived from half-cycle inflection points in the acceleration trace. Averaging the half-cycle values of H based on target side revealed clear differences in the big and small targets in the mixed target condition. What the half-cycle H-values may represent is an increase in dissipation of stored mechanical energy over the big target with no difference over the small target in the mixed condition. In this context, this difference in energy dissipation is more evidence supporting the idea that the optimal solution to the task consisted of both discrete and cyclical components.

An interesting finding in the research on non-repetitive aiming to mixed target pairs in sequence is the one-target advantage. The one-target advantage is as follows: when two targets occur in sequence but the hand does not reverse direction over the first target, MT to the first target is longer than the MT to the first target when in isolation (Adam et al. 1995; Adam et al. 2000). However, the one-target advantage disappears when a movement reversal occurs over the first target, such that the hand moves back towards the starting location (Lajoie and Franks 1997; Adam et al. 2000). In both experiments, the one-target advantage associated with movement reversals did not occur. A possible explanation is that the very small target eliminated the integration of the small and big target movements (Adam et al. 2000). The acceleration–deceleration, harmonicity, and dwell time results, however, all support the hypothesis that the movements to the big and small target were integrated or functionally linked. A more plausible explanation is that longer MTs to the big target in the mixed pair were a trade-off to the shorter MTs to the small target in the mixed pair, such that the cyclical unit could be linked to the discrete unit to provide the most optimal solution. This explanation is consistent with the idea that task constraints, i.e., the specific combination of IDs, shape the parameterization of the functional linkage between the basic units of actions.

Practice effects

With practice the tendency was for the motion to become more cyclical in both the 1D and 2D mixed target conditions. Practice produced a systematic increase in the full-cycle H-value away from the value of H=0.5 that Guiard (1997) put forth as the demarcation point between discrete and cyclical motion. This suggests that while the task initially produced a competition that utilized components of both discrete and cyclical solutions, the bias with practice was to a more cyclical solution, especially in the 1D task. The half-cycle H-values from the 1D task support this conclusion and localize the change associated with practice to movement towards the small target. Another prominent practice result was the decrease in adjustment dwell time ($T_{adj}$) to the small target in the mixed target condition in the 2D task. This suggests that practice lead to better initial trajectory estimates requiring less corrective action before target strike, further supporting a more prominent role of vision before target strike than after (Ricker et al. 1999; Cullen et al. 2001).

Models of reciprocal aiming:
fixed point and limit cycle attractors

The results from both experiments demonstrate that the mixed target condition did not break the end-effector's trajectory into discrete movement primitives that are independently controlled. This suggests that information-processing models emphasizing concatenation of discrete primitives may not be sufficient models for the results in the mixed target condition, although they might work quite well in the small target case when movement adjustments occur before target strike (Crossman and Goodeve 1963; Meyer et al. 1988; Plamondon and Alimi 1997). Recently, Mottet and Bootsma (1999) have developed an oscillator model of the end-effector's dynamics in a repetitive aiming task similar to our experiment 1. However, while the Mottet and Bootsma model covers a large range of IDs, 3 <ID <7, it breaks down when the ID drops below 3. For both experiments, the high ID was 2.4, and discrete motion predominated. This suggests that an oscillator model would have problems accounting for the results from the small target condition as well as possibly the mixed target condition that consists of both discrete and cyclical movement components. This does not mean that oscillator models might not be able to account for some mixed target conditions. Recent work employing a mixed target condition in a 2D elliptical motion task has shown that the end-effector's trajectory in a mixed target case can be reproduced with a limit cycle oscillator (Mottet and Bootsma 2001). An examination of the Hooke portraits from the 2D elliptical task clearly shows no equilibrium point type behavior. Three important differences in the mixed target condition in the 2D elliptical work and the work presented might account for this: first, the IDs in the elliptical task ranged between 3 and 7, second, the continuous tracing of an elliptical orbit is not characterized by abrupt movement reversals, and third, the mixed targets were not paired on the same axis.

A resolution to the above issue of combining discrete and cyclical action units might be through the idea that discrete and cyclical units are different attractive states of a nonlinear dynamical system (Schöner 1990; Sternad et al. 2000). The combination of both discrete and cyclical units as a model of discrete motion has been proposed by Schöner (1990) to account for tasks similar to the tasks used in both experiments. Based on Schöner's model, a discrete motion may be viewed as the translation of the end-effector between two stable fixed-point attractors. The interesting feature of the proposed model is that the trajectory of the end-effector between the two fixed-points is along a limit-cycle trajectory that has been made stable through a parameter representing the intention to move (Schöner 1990). The data presented suggest that the motor system produced a solution containing both discrete and cyclical motion in the mixed target condition. As a result of the differences in target ID in the mixed condition, the solution was not between two fixed-point attractors connected with a limit-cycle trajectory. Instead, the solution seems to have taken the form of a stable fixed-point attractor associated with the end-effector position over the small target (high ID) out onto a limit-cycle trajectory that contained within it a strike on the big target (low ID). Thus, discrete and cyclical units are represented in the form of attractive states of a nonlinear dynamical system that can be functionally linked.

The idea of combining discrete and cyclical units raises the question of how many cycles before a movement is considered cyclical. The practice data provide some insight into this issue of number of cycles. Early in practice, the full-cycle H-values around 0.5 indicate that end-effector motion was on the cusp between discrete and cyclical motion, and support the idea that end-effector motion might have been anchored on a fixed-point attractor over the small target but that the end-effector trajectory also had dynamics that might represent a stable limit-cycle when moving across the large target. This suggests that the repetitive motion in the mixed target condition might have consisted of a chain of linked cycles with each cycle being itself independent. From practice block 1 to block 5 in the mixed target condition, the full-cycle H-values increased significantly in both experiments, so that with practice the dynamics of the overall motion was becoming more cyclical. Thus, the difference in the end-point spatial constraints initially produced a cyclical solution with cycles of 1 (Guiard 1997). However, the interesting feature is that the individual cycles appear to be connected with a fixed-point attractor. This suggests that each cycle early in practice is probably initialized separately from other cycles, but with practice the cycles are sequenced together to produce rhythmic motion characterized by its own unique dynamics.

The mixed target condition produced a competition between discrete and cyclical units that resulted in a movement chunk. In the mixed target condition, chunking may be viewed as a functional linkage between a fixed point and limit cycle attractor. Similarity in movement segments is not in terms of shared kinematics in a context-dependent environment that leads to the chunking (Rand et al. 1997; Rand and Stelmach 2000); instead, similarity may be in terms of stability of the different attractor states such the motor system tries to achieve some optimal stability based on the task. Some evidence for this may be found in the MT, acceleration–deceleration data, and end-point variability data. Shorter MTs to the small target in the mixed target condition could have produced greater end-point variability. However, the increase in MT characterized as the deceleration phase points to the role of visual feedback processing in ensuring target strike and reducing end-point variability. The longer MTs to the big target suggest that movement slowing might be associated with making this segment of the motion more stable, consistent with less variability in end-point position for the big target in the mixed condition. Although the experiments presented cannot conclusively support the above ideas, perturbation of end-effector motion and examination of relaxation times would provide important information on the change in the stability of cyclical and discrete units when functionally linked together in a mixed target task.

## Conclusions

The above description of functionally linked discrete and cyclical units of action raises two important theoretical control issues. The first is related to the issuing of discrete and cyclical control signals in sequence or parallel, and the second is related to the role of practice in possibly modifying the issuing of discrete and cyclical control signals. For example, Adamovich et al. (1994) argued for sequential issuing of discrete and cyclical control signals to the same limb, whereas Sternad et al (2000) argued for simultaneous activation of control signals. In the mixed target task, a case for sequencing of control signals may be developed from the idea that cyclical motion was anchored to an equilibrium point, especially in block 1. A case for simultaneous issuing of control signals may be seen in the changes in the acceleration profile and harmonicity that occur with practice. That is, if the movement becomes more cyclical with practice, then this may represent a switch from sequential to parallel issuing of the commands in order to tune the interaction between estimation-planning processes and feedback correction processes. The experiments presented highlight the importance of addressing the above issues through further studies that investigate how the central nervous system combines discrete and cyclical units of action to produce complex goal-directed skills.

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