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Discrete and cyclical movements: unified dynamics or separate control?

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Abstract

In the literature on motor control, three theoretical perspectives on the relation between discrete and cyclical movements may be discerned: (a) cyclical movements are concatenated discrete movements; (b) discrete movements are a limiting case of cyclical movements, and (c) discrete and cyclical movements are motor primitives that may be combined but are irreducible to each other. To examine the tenability of these perspectives, 16 participants performed cyclical and discrete (flexion and extension) reaching movements of various amplitudes to differently sized targets. The kinematic properties of the recorded movements were analyzed and compared in detail. The cyclical, ongoing movements differed markedly from the discrete movements as well as from the first and last half-cycles of a bout of cyclical movements, especially in terms of their symmetry ratio. These effects were largely independent of amplitude, target size and movement direction (flexion–extension). The results obtained ruled out perspective (a) and, in principle, left open perspectives (b) and (c). However, the observed kinematic features were not readily accounted for by the specific dynamical models that have been proposed under perspectives (b) and (c). Future modeling attempts should explicate the dynamics of initiation and abortion of both discrete and cyclical movements.

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1. Introduction

In the study of motor control, discrete and cyclical movements still constitute largely separate domains of inquiry. Research on discrete movements (e.g., prehension, aiming) traditionally focuses on topics like motor planning, trajectory formation and online control. Since the pioneering work of Woodworth (1899), a key question in this area of research has been the degree to which movement trajectories are the product of either open-loop or closed-loop control. In contrast, research on cyclical movements is concerned with issues like rhythm or pattern generation (timekeeping), and spatiotemporal stability, both in terms of individual limb movements and their coordination (see, e.g., Haken, Kelso, & Bunz, 1985; Kelso, 1995; von Holst, 1973).

Due to this divergence of interest, current models of discrete and cyclical movements differ greatly, both conceptually and formally. At present, however, there is a clear upsurge of interest in the relationship between discrete and cyclical movements. Roughly speaking, three theoretical perspectives can be distinguished in the literature on motor control. The first is that discrete movements are foundational for cyclical movements in the sense that cyclical movements are concatenations of discrete movements. The second posits conversely that oscillatory, cyclical movements are foundational and that discrete movements are in fact a limiting case of cyclical movements and may be conceived as half-cycles. These two contrasting positions share the prospect that, in principle, discrete and cyclical movements may be reduced to a single concept or theoretical account. This possibility is refuted by the third viewpoint, according to which discrete and cyclical movements represent different, essentially unrelated, classes of movement, involving distinct planning mechanisms.

In the remainder of this introduction, we will elaborate these theoretical perspectives and their empirical basis (or the lack thereof) in more detail. From this discussion, it will become apparent that the empirical basis for theorizing about the relation between discrete and cyclical movements is remarkably small with respect to the concatenation and oscillator theory and incomplete in general. This observation motivated the experiment reported in the present article, which was performed to help evaluate the tenability of the three identified perspectives by means of a detailed comparison of the kinematic features of discrete and cyclical reaching movements.

The predilection to view cyclical movements as concatenations of discrete movements is particularly prevalent in the study of the neural basis of movement planning and trajectory formation. For example, in modeling handwriting movements, Morasso (1986) assumed that the individual pen strokes are the units of control, and that cursive, cyclical writing results from concatenation of these individual strokes. Surely, if one starts from the assumption that the brain plans and executes discrete elements or 'primitives', then it is a natural step to analyze and model cyclical movements as the result of a series of such discrete primitives. From this (often implicit) assumption much emphasis has been placed on techniques for the segmentation of continuous data, and the subsequent modeling of the control of the identified discrete segments (see, e.g., Viviani, 1986). Importantly, the key assumption behind the notion of concatenation is that discrete movements may be braided together into a sequence of movements without affecting their identity. Thus, according to the concatenation perspective, the kinematic properties of cyclical movements are essentially identical to those of discrete movements.

The concatenation interpretation of cyclical movements has been criticized on the ground that it would imply a waste of stored elastic energy in muscles and tendons once every half-cycle (Guiard, 1993). Furthermore, based on experimental studies involving both discrete and cyclical movements, Smits-Engelsman, van Galen, and Duysens (2002) and Buchanan, Park, Young, and Shea (2003) concluded that the concatenation theory could not account for the differences they found between discrete and cyclical movements.

The proposed alternative theory, viz. that discrete movements are a limiting case of cyclical movements, originated from a line of research with a primary focus on cyclical movements and their coordination, namely dynamical systems theory or coordination dynamics (see Beek, Peper, & Stegeman, 1995; Kelso, 1995, for review). A key element in this approach has been the understanding of cyclical movements as stable self-sustaining oscillators or limit cycles (see, e.g., Beek & Beek, 1988; Beek, Rikkert, & van Wieringen, 1996; Beek, Schmidt, Morris, Sim, & Turvey, 1995; Haken et al., 1985; Kay, Kelso, & Saltzman, 1987; Kelso, 1981). From this perspective, a discrete movement may be understood as a limiting case of a cyclical movement, that is, half a cycle. Unlike the concatenation theory, the oscillator theory posits that ongoing cyclical movements do not have to be assembled afresh every half cycle, but rather that principles of saving and releasing of elastic energy are operative that help sustain the cycling; after all, oscillations can be conceived of as trade-offs between kinetic and potential energy (Guiard, 1993). Only when a bout of cyclical movements is started or stopped, this continuous flow of energy has to be initiated or aborted. It follows from this theoretical perspective that cyclical, ongoing movements should not only differ from discrete movements (involving an initiation and a cessation) but also from the first half cycles of episodes of cyclical movements (involving an initiation) and the last half cycles of episodes of cyclical movements (involving a cessation). Conversely, discrete movements may be expected to have at least certain resemblances with both the first and the last half-cycle of bouts of cyclical movements.

Some empirical support for the oscillator theory came from a study by Zaal, Bootsma, and van Wieringen (1999), who showed that the kinematics of discrete reaching movements towards both stationary and moving targets could be accounted for in terms of a dynamical system similar to the one proposed by Schöner (1990) to describe both discrete and cyclical movements. Furthermore, Latash, Scholz, Danion, and Schöner (2002) concluded that their experimental results regarding discrete and oscillatory isometric force production tasks were more compatible with the oscillator theory, while Guiard (1993, 1997) provided evidence for the validity of the oscillator theory in a study comparing the harmonicity of discrete and cyclical movements. In general, however, there is a definite need for strengthening the empirical basis of this theory, in particular with respect to the notion of the discrete movements resembling the first and last cyclical movements.

The third, most recent, perspective in the literature is the two primitives perspective, in which discrete and cyclical movement are viewed as two motor primitives (de Rugy & Sternad, 2003; Ijspeert, Nakanishi, & Schaal, 2003; Sternad, de Rugy, Pataky, & Dean, 2002; Sternad & Dean, 2003; Sternad, Dean, & Schaal, 2000; Wei, Wertman, & Sternad, 2003). On this perspective, discrete and cyclical movements are irreducible to each other, and cannot be captured by a single theoretical concept as they involve essentially different mechanisms for movement planning and execution. Evidently, for this theoretical position to hold, discrete and cyclical movements must differ from each other along at least a number of dimensions. To examine the hypothesis that discrete and cyclical movements are movement primitives that, as a consequence, may be combined, Sternad et al. (2000) studied the performance of discrete movements on top of cyclical movements, and concluded that the results were consistent with their theoretical assumption. Additional empirical support for the two primitives theory came from several subsequent studies (e.g., Buchanan et al., 2003; Smits-Engelsman et al., 2002).

The preceding overview illustrates that, whereas the concatenation theory has broadly been discarded as a viable account, both the oscillator theory and the two primitives theory have received empirical support. However, in the experimental studies published to date, discrete movements were compared to ongoing cyclical movements and not to the first and last movements of a bout of cyclical movements. In this regard, the empirical evidence regarding the relation between discrete and cyclical movements currently available is still incomplete. Especially in light of the implicit predictions of oscillator theory, comparison of the discrete movement to the first and last cycle of a bout of cyclical movements could be expected to provide more insight into the relation between discrete and cyclical movements. In the present study, we therefore sought to expand the empirical basis for resolving the discrete–cyclical issue along those lines. To this aim, we compared key kinematic properties (i.e., peak speed, symmetry ratio, movement time, jerkiness, peak acceleration, peak deceleration) of discrete and cyclical reaching movements, with the latter category being subdivided into first, ongoing and last cyclical movements.

Considering the fact that these movement types have different boundary conditions (i.e. different initiation–cessation requirements), one might already expect certain kinematic differences on theoretical grounds. In idealized form, discrete movements are known to have a bell-shaped velocity profile (implying that position, velocity and acceleration are zero at the start and the end of the movement) and cyclical movements a sinusoidal velocity profile (implying that acceleration is not zero at the turning points). For this reason, a bout of cyclical movements may be expected to start with the left half of a bell (starting with acceleration zero), continue with a sinusoid and end with the right half of a bell (ending with acceleration zero). In comparing the kinematic properties of the four movement types distinguished, it is important to take this issue into account, as we will do in the general discussion of the results.

Besides movement type, several other variables (e.g. target size, movement amplitude, flexion/extension) were manipulated to ensure comparison of discrete and cyclical movement across a wide range of conditions. The effects of these variables on the kinematic properties were investigated and, when possible, compared to the effects found in other studies to verify the external validity of the experiment.

2. Method

2.1. Subjects

Sixteen normal, right-handed volunteers (2 men, 14 women, 23–29 years of age) participated in the experiment after having given their written informed consent.

2.2. Procedure

The participants were instructed to make discrete and cyclical reaching movements between two targets of equal size. Besides target size, movement amplitude and movement direction (flexion vs. extension) were varied to be able to compare the kinematics of discrete and cyclical movements across a wide range of experimental conditions. The participant was seated comfortably at a table so that his or her right arm could reach freely over the surface. Two targets were placed on the tabletop, one close to and the other further in front of the participant, approximately in line with the right shoulder. The participant was instructed to adjust his or her posture until reaching from the one to the other target felt natural and could be performed fluently. The targets consisted of identical flat black circles (painted on a white background) with a diameter of 12 or 18 mm. The distance between the targets was 20 or 40 cm, resulting in four target size–movement amplitude combinations with indices of difficulty ranging from 4.47 to 6.06. The experiment consisted of four sessions, in which either cyclical or discrete, either flexion or extension movements were performed as fast and as accurately as possible (for example: flexion-cyclical; flexion-discrete; extension-cyclical; extension-discrete). As there were four permutations of cyclical and discrete sessions, and participants started with either two flexion or two extension sessions, there were eight different session orders. These session orders were assigned randomly to the 16 participants, with each session order occurring twice. Within each session the four target size–movement amplitude combinations were presented in random order to the participant and each combination was repeated 5 times, resulting in $2 \times 2 \times 4 \times 5 = 80$ trials for each participant. In the cyclical movement condition, the participants were instructed to put the tip of their right index-finger on the starting position (depending on the direction condition) and to commence making fluent cyclical reaching movements between the two targets shortly after a start signal was given by the experimenter. The participants were further instructed to touch the targets lightly and to minimize the number of misses, while still performing the task as fast as possible. They were given the opportunity to practice whenever the conditions changed until, in their judgment, they had found their maximal speed for that particular condition. After approximately 15 cycles the participants received a stop-signal from the experimenter. The participants were instructed not to stop immediately upon hearing the signal, but rather to perform a few more cycles and to stop whenever they wished, with the proviso that they had to stop on the second target (i.e., the one they had not started from), to ensure that the last cyclical movement would be comparable to the discrete and first cyclical extensions or flexions. Furthermore, they were instructed not to adjust their finger position after they had stopped, even though they might not have landed precisely on the middle of the target. Another signal was given by the experimenter to indicate that the participant had to return to the starting position. In the discrete movement condition, the participants were instructed again to put the tip of their right index-finger on the starting position and perform a fluent discrete reaching movement (again, as fast as possible) towards the second target shortly after a start signal given by the experimenter. As before, no correction of the final position was allowed and a signal was given to indicate return to the starting position.

2.3. Data acquisition

Kinematic data were collected using an OPTOTRAK 3020 movement registration system (Northern Digital, spatial accuracy <0.1 mm). A camera unit (sensor beam) was positioned in front of the participant at a distance of about 2 m from the starting position and 1 m above the surface of the table. A single infrared light emitting diode (IRED) was attached to the nail of the right index-finger. Sampling frequency was 200 Hz. Data collection was initiated just before the start signal and ended just after movement termination. Calibration was performed such that the x-axis ran parallel to the line passing through the two targets.

2.4. Data reduction

High frequency noise was removed from the data by applying a 2nd order low-pass Butterworth filter with a cut-off frequency of 10 Hz. If possible, outliers were corrected by interpolating between neighbouring samples. However, in 22 of all 1280 trials the outliers could not be fixed because too many of them had occurred in a row; these trials were removed from the dataset. After these reductions, a total of 1258 trials remained available for analysis. The initiation and termination of the discrete and cyclical reaching movements were defined as the moment at which the movement velocity exceeded, respectively fell below 50 mm/s. Based upon these moments, movement time was calculated. The position data were differentiated by means of a finite differences algorithm to obtain velocity and acceleration data, respectively. A peak-picking algorithm was subsequently used to determine peak speed and peak acceleration and deceleration of each individual movement. The symmetry ratio was defined as the acceleration time (i.e., the time from movement initiation to peak speed) divided by the total movement time. Jerkiness was determined by calculating the normalized integral jerk of the velocity profiles. To this end, the velocity profiles were normalized over time and speed (e.g., rescaled to a timescale from 0 to 1 and divided by peak speed), after which the integral of the second derivative of the velocity profile was taken. For each participant and each of the kinematic features of interest, the values for the first cyclical, ongoing cyclical, and last cyclical movements were calculated per trial. For the cyclical, ongoing movements, the kinematic features were determined for the three middle cycles of the bout and then averaged to obtain better estimates. In addition, the values for the discrete trials were determined. The so determined values of the kinematic variables were averaged over the five repetitions for each experimental condition to obtain reliable estimates for the subsequent statistical analysis. For the movement time data, not only the means were calculated, but also the corresponding standard deviations.

The effects of the experimental conditions on the dependent variables were analyzed using a repeated measures ANOVA with four within-subject factors: movement type (discrete, first cyclical, ongoing cyclical, last cyclical movements), target size (12, 18 mm), movement amplitude (20, 40 cm) and movement direction (extension, flexion). Sphericity was assumed for values of epsilon greater than 0.75. If sphericity could not be assumed, the Huynh-Feldt correction was used to determine significance. When a significant effect on a within-subject factor was found, the means obtained from the repeated measures analysis were subjected to paired Student *t*-tests with Bonferoni corrections to examine the origin of the effect. The conventional significance level of $p < 0.05$ was adopted (or lower in the case of Bonferoni corrections).

3. Results

3.1. Movement kinematics

The first step in analyzing the data consisted of visual inspection of the velocity profiles and phase portraits. Fig. 1 shows the velocity profile, the acceleration profile and the phase portrait of a single participant for the discrete movements, the cyclical, ongoing movements and the first and last half-cycle of the cyclical movements. As can be seen, the discrete, the first cyclical and last cyclical movements tend to differ from the cyclical, ongoing movements. This was commonly observed in the data across all participants, and was confirmed statistically, as will be apparent in the following.

3.2. Statistical results

Table 1 provides an overview of all significant main effects that were found. As can be seen, object size, amplitude, movement direction and movement type all affected the kinematic variables of interest in at least certain regards. Importantly, movement type had a significant effect on all dependent variables except peak deceleration, indicating the presence of systematic, non-incidental differences in the kinematics of the four movement types distinguished. In order to facilitate the description and the analyses of these effects in the remainder of this results section, Fig. 2 shows the bar charts corresponding to the effects of movement type on the kinematics.

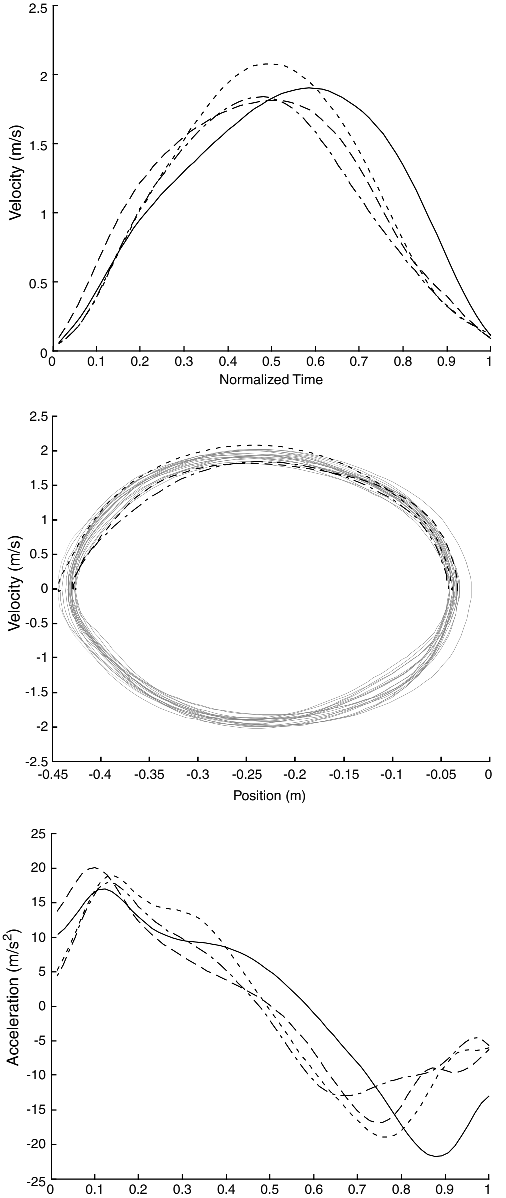

Fig. 1. Velocity profile (top), phase portrait (middle) and acceleration profile (bottom) for discrete movements (···) and the corresponding first (-.-), ongoing (solid, gray in phase portrait) and last (---) cyclical movements. These graphs represent the data of a discrete and a cyclical extension trial from a single participant in order to illustrate the kind of data that were analyzed in this study.

Table 1
Overview of main effects

Kinematic variables	Movement type	Target size	Amplitude	Direction
Peak speed	***	**	***	–
Symmetry ratio	***	***	***	***
Movement time (MT)	*	***	***	–
SD of MT	***	–	***	–
Normalized integral jerk during acceleration	***	–	***	–
Normalized integral jerk during deceleration	***	–	***	–
Peak acceleration	*	**	***	**
Peak deceleration	–	***	***	**

Non-significant effects are indicated by –, significant effects by *($p < 0.05$), **($p < 0.01$), and ***($p < 0.001$).

As explained in Section 1, the main purpose of the effects of target size, amplitude and movement direction was to create a broad range of conditions and to evaluate the external validity of the experiment. Therefore, for each kinematic feature, we will first address the (main and interaction) effects of movement type and then briefly discuss the other effects.

3.2.1. Peak speed

Peak speed was affected significantly by movement type ($F(4,16) = 18.358$, $p < 0.0001$). Post hoc analyses revealed that the discrete movements had the highest peak speed, followed by the ongoing cyclical movements and that the first and last cyclical movements had the lowest peak speeds; only the difference between the latter two values was not significant (see Fig. 2). A significant interaction effect of movement type and amplitude ($F(4,16) = 23.920$, $p < 0.0001$) occurred because the effect of movement type on peak speed was more pronounced for the larger amplitudes.

Peak speed was also affected significantly by amplitude ($F(4,16) = 928.491$, $p < 0.0001$) and target size ($F(4,16) = 13.977$, $p < 0.005$). Consistent with previous empirical results (e.g., Bootsma, Marteniuk, Mackenzie, & Zaal, 1994; Bootsma, Mottet, & Zaal, 1998; Jakobson & Goodale, 1991; Zaal et al., 1999), peak speed was higher for larger amplitudes (1.89 (±0.01) vs. 1.20 (±0.01) m/s; standard deviation between brackets) and targets (1.57 (±0.01) vs. 1.52 (±0.01) m/s). In addition, a significant interaction effect occurred between amplitude and direction ($F(4,16) = 10.452$, $p < 0.01$) because the effect of amplitude on peak speed was stronger for flexion than extension movements.

3.2.2. Symmetry ratio

Movement type had a significant effect on the symmetry ratio ($F(4,16) = 23.591$, $p < 0.0001$). Post hoc analysis of this effect revealed that the symmetry ratios of the discrete movements did not differ significantly from those of the first and last cyclical movements, and that the symmetry ratios of the cyclical, ongoing movements were significantly higher than those of the other three movement types (see Fig. 2). These results confirmed the observation that the discrete movements, as well as the first and

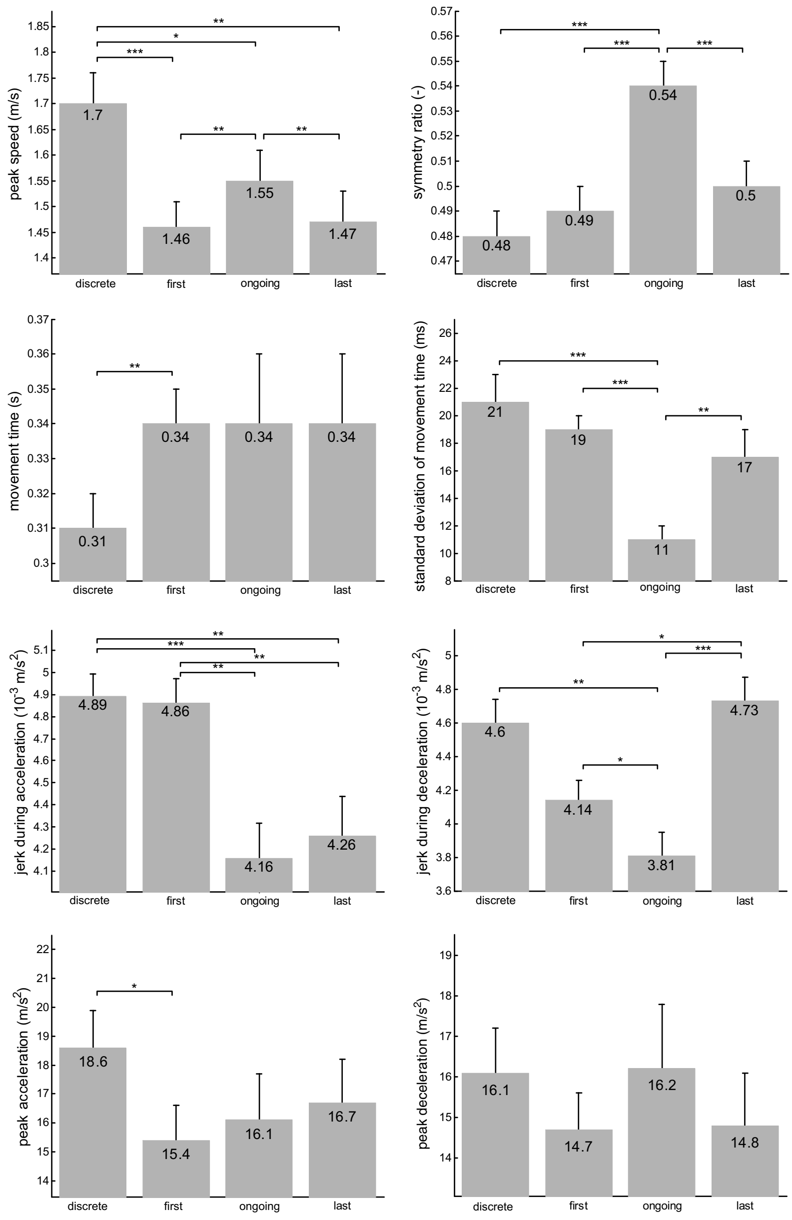

Fig. 2. The effects of movement type (horizontal axes) on all kinematic variables of interest (vertical axes). Except for peak deceleration, all kinematic variables were significantly affected by movement type. Significant differences as indicated by post hoc *t*-tests are indicated by $^{*}(p < 0.05)$, $^{**}(p < 0.01)$ and $^{***}(p < 0.001)$.

last cyclical movements, tended to deviate from the band in the phase plane formed by the cyclical, ongoing movements.

Target size ($F(4,16) = 20.141$, $p < 0.001$), amplitude ($F(4,16) = 40.528$, $p < 0.0001$) and direction ($F(4,16) = 33.755$, $p < 0.0001$) also had a significant effect on the symmetry ratio. The symmetry ratio increased with increasing target size (0.50 (±0.01) vs. 0.51 (±0.01)), decreased with increasing amplitude (0.51 (±0.01) vs. 0.49 (±0.01)), and was higher in flexion than extension movements (0.52 (±0.01) vs. 0.48 (±0.01)). The effect of movement direction was consistent with the results of Mirkov, Milanovic, Ilic, and Jaric (2002).

3.2.3. Movement time and standard deviation of movement time

The effect of movement type on movement time was significant ($F(4,16) = 5.259$, $p < 0.05$). Post hoc analysis revealed that the movement times of the discrete movements were significantly shorter than those of the first cyclical movements (see Fig. 2). Other than that, no significant differences between discrete, first cyclical, ongoing cyclical and last cyclical movements were found. A significant interaction effect of movement type and amplitude ($F(4,16) = 16.705$, $p < 0.0001$) revealed that the effect of movement type was more prominent at larger amplitudes.

In addition, significant effects of target size ($F(4,16) = 25.201$, $p < 0.0001$) and amplitude ($F(4,16) = 440.03$, $p < 0.0001$) on movement time were found in line with Fitts' Law and previous empirical results (e.g., Bootsma et al., 1994; Bootsma et al., 1998; Jakobson & Goodale, 1991; Zaal et al., 1999): movement time increased with increasing amplitude (0.29 (±0.01) vs. 0.37 (±0.01) s), and decreased with increasing target size (0.34 (±0.01) vs. 0.32 (±0.01) s). A significant target size-by-amplitude effect ($F(4,16) = 5.690$, $p < 0.05$) was found, because the effect of target size was slightly more pronounced at larger amplitudes.

With regard to the standard deviation of movement time, a significant effect of movement type ($F(4,16) = 13.867$, $p < 0.0001$) was observed. Post hoc analysis showed that the standard deviations of movement time of ongoing cyclical movements were significantly smaller than those of discrete, first cyclical and last cyclical movements (see Fig. 2).

Furthermore, significant effects of amplitude ($F(4,16) = 33.883$, $p < 0.0001$) and target size-by-direction ($F(4,16) = 7.63$, $p < 0.05$) were found. The amplitude effect occurred because the standard deviation of movement time was smaller for smaller amplitudes (15 (±1) vs. 19 (±1) ms). The interaction effect revealed opposite effects of target size for extension and flexion movements: Whereas the standard deviation of movement time increased with target size for flexion movements (15 (±1) vs. 18 (±1) ms), the opposite was true for the extension movements (18 (±1) vs. 17 (±1) ms).

3.2.4. Normalized integral jerk

The jerkiness during acceleration, as indexed by the normalized integral jerk, was affected significantly by movement type ($F(4,16) = 18.920$, $p < 0.0001$). Post hoc *t*-tests revealed that all differences between movement types were significant, except that between the discrete movements and the first cyclical movements and that between the cyclical, continuous movements and the last cyclical movements (see

Fig. 2). This result indicates that the acceleration parts of the ongoing and last cyclical movements were smoother than those of the discrete movements and the first cyclical movements. A significant interaction between movement type and amplitude ($F(4,16) = 5.874$, $p < 0.01$) revealed a more pronounced movement type effect at larger amplitudes. A significant interaction effect between movement type and direction ($F(4,16) = 4.726$, $p < 0.05$) showed that this effect was more pronounced for extension movements.

Amplitude ($F(4,16) = 53.763$, $p < 0.0001$) also had a significant effect on jerkiness during acceleration. This effect occurred because jerkiness during acceleration increased with increasing amplitude (4.35 (±0.12) vs. 4.73 (±0.12) m/s^2).

As regards the jerkiness during deceleration, the effect of movement type was significant ($F(4,16) = 15.460$, $p < 0.0001$). Post hoc analysis revealed that, on average, the jerkiness during deceleration was significantly lower in the ongoing cyclical movements than in the other movement types. Furthermore, the jerkiness during deceleration of the first cyclical movements was lower than for the last cyclical movements (see Fig. 2).

The jerkiness during deceleration was affected significantly by amplitude ($F(4,16) = 33.09$, $p < 0.0001$), showing an increase in jerk for larger amplitudes (4.01 (±0.08) vs. 4.63 (±0.14)). Besides a significant amplitude-by-direction interaction ($F(4,16) = 4.573$, $p < 0.05$), which occurred because the effect of amplitude was stronger for the extension movements, a significant target size-by-direction effect ($F(4,16) = 10.550$, $p < 0.01$) and a significant three-way target size-by-amplitude-by-direction effect ($F(4,16) = 5.842$, $p < 0.05$) were found. The former effect occurred because the effect of target size was opposite for flexion and extension movements, similar to the effect that was found for the standard deviation of movement time. Increasing the target size had a decreasing effect on jerkiness during deceleration of extension movements (4.40 (±0.14) vs. 4.34 (±0.13)) and an increasing effect on jerkiness during deceleration of flexion movements (4.14 (±0.14) vs. 4.39 (±0.13)). The significant three-way interaction occurred because the aforementioned interaction effect mainly occurred in the larger amplitude condition.

3.2.5. Peak acceleration and peak deceleration

A significant movement type effect on peak acceleration ($F(4,16) = 5.226$, $p < 0.05$) was revealed. Post hoc *t*-tests on this effect showed that peak acceleration of the discrete movements was higher than for first cyclical movements, in line with the effect on movement time. No other significant differences between discrete, first cyclical, ongoing cyclical and last cyclical movements were present (see Fig. 2). A significant interaction effect ($F(4,16) = 16.307$, $p < 0.0001$) between movement type and amplitude revealed that, at larger amplitudes, this effect was more pronounced.

Peak acceleration was affected significantly by amplitude ($F(4,16) = 124.775$, $p < 0.0001$), target size ($F(4,16) = 19.178$, $p < 0.005$) and direction ($F(4,16) = 16.846$, $p < 0.005$). Peak acceleration increased with both target size (16.1 (±1.2) vs. 17.3 (±1.3) m/s^2) and amplitude (14.7 (±1.2) vs. 18.7 (±1.4) m/s^2), and was lower for flexion than extension movements (15.5 (±1.3) vs. 17.8 (±1.3) m/s^2).

Significant interaction effects were found between movement type and amplitude ($F(4,16) = 16.536$, $p < 0.005$) and between movement type and direction ($F(4,16) = 16.536$, $p < 0.005$). Whereas the former interaction effect was not readily interpretable, the latter suggested that for flexion movements, the peak deceleration of ongoing cyclical movements was higher than for the first and last cyclical movements. No other significant differences were detected.

Peak deceleration was affected significantly by target size ($F(4,16) = 32.460$, $p < 0.0001$), amplitude ($F(4,16) = 162.691$, $p < 0.0001$), and direction ($F(4,16) = 16.536$, $p < 0.005$). These effects indicated that peak deceleration increased with increase in target size (14.8 (±1.1) vs. 16.1 (±1.2) m/s^2), increase in amplitude (13.9 (±1.1) vs. 17.0 (±1.2) m/s^2), and for flexion compared to extension (14.3 (±1.1) vs. 16.6 (±1.3) m/s^2).

4. Discussion

The goal of the present study was to examine the tenability of three theoretical perspectives on the relation between discrete and cyclical movements, here referred to as the concatenation theory, the oscillator theory and the two primitives theory. To this aim, we measured and compared several key kinematic features of discrete and cyclical reaching movements. Within the latter class of movements, we further distinguished between the first and the last cyclical movements of a bout of cyclical movements, and the continuous, ongoing cyclical movements in between. In the following, after a brief recapitulation of the main findings, we first discuss the results obtained and the extent to which they can be interpreted as a consequence of the differences in boundary conditions of the four movement types (see Section 1). Finally, we discuss the implications of the results for the three theoretical perspectives of interest.

In the present experiment, numerous significant effects of amplitude, target size, direction and movement type were found. The significant effects of amplitude, target size and direction are important in two regards. First, they reflect that the goal of the experiment to compare discrete and cyclical movements across a broad range of kinematic variations was accomplished. Second, the fact that the effects of these manipulations were largely consistent with those in previous reports (e.g., Bootsma et al., 1994; Bootsma et al., 1998; Jakobson & Goodale, 1991; Mirkov et al., 2002; Zaal et al., 1999) testifies to the external validity of the experiment. However, given that the present study's main focus was to compare discrete and cyclical movements, the remainder of the discussion will concentrate on the main effects of movement type and interaction effects in which movement type was included.

Movement type had a significant effect on all kinematic variables except peak deceleration, and was often implicated in significant interaction effects. The kinematic properties of discrete movements differed significantly from those of ongoing cyclical movements, except movement time, peak acceleration and peak deceleration during flexion. Furthermore, in terms of peak speed, symmetry ratio, standard deviation of movement time, jerk during deceleration, and peak deceleration during flexion, the ongoing cyclical movements differed significantly from both the first and last cyclical movements. Discrete movements tended to resemble the first cyclical movements in terms of symmetry ratio, standard deviation of movement time, jerkiness and peak deceleration, and the last cyclical movements in terms of symmetry ratio, movement time, standard deviation of movement time, jerk during deceleration, peak acceleration and peak deceleration. The first and last cyclical movements did not differ significantly in terms of peak speed, symmetry ratio, movement time, standard deviation of movement time, peak acceleration and peak deceleration. Interaction effects involving movement type were found predominantly in combination with amplitude, because the effects of movement type were more pronounced for the larger than for the smaller amplitudes.

The combined effects of movement type on peak speed, movement time and peak acceleration revealed that the discrete movements were executed faster than the cyclical movements, particularly the first cyclical movement, under the same task constraints. This could simply have been due to the participants realizing that the cyclical trial would be more fatiguing than the discrete trials, which could have prompted them to adopt a lower speed. The observed effect on the symmetry ratio implies that the deceleration phase of the discrete movements and the first and last cyclical movements was longer than that of the cyclical, ongoing movements. Furthermore, compared to the ongoing cyclical movements, these movements were jerkier and more variable in duration. The resemblance between the discrete movements and the first cyclical movements could be explained by the fact that both types of movement were performed without feedback from previous movements, making it more difficult to reach accurately and forcing the participant to rely more on the quality of energy insertion into the movement (i.e. the 'initial impulse'). Conversely, the fact that the symmetry ratio of the last cyclical movements was smaller than that of the cyclical, ongoing movements might be interpreted to imply that, while energy could have been transferred from previous movements into the last, this energy had to be dissipated in order to come to a complete standstill at the target, thus requiring a longer deceleration phase. Finally, the incongruent effects of movement type on the two measures for jerkiness indicate that it is important to distinguish between acceleration and deceleration parts of the movement. Unlike the effects on the symmetry ratio and the standard deviation of movement time, the jerkiness during the acceleration phase of the last cyclical movements resembled that of the cyclical, ongoing movements, whereas the jerkiness during the deceleration phase of the last cyclical movements resembled that of the discrete movements. Apparently, the last cyclical movements started like any other cyclical, ongoing movement, whereas their deceleration profile clearly differed, which is consistent with our earlier interpretation that the distinctive aspect of the last cyclical movements resided in the dissipation of energy when settling down on the target.

As explained in Section 1, certain kinematic differences between the four distinguished movement types may be expected because of the inherent differences in boundary conditions. However, the effects we found in the data are not simply the consequences of this fact. This can be illustrated by comparing the observed kinematic effects to the effects that would be expected from the idealized movement trajectories considered in Section 1 (i.e. bell-shaped velocity profile vs. sinusoid). In principle, this thought experiment could be developed for all kinematic features of interest, but we confine ourselves to symmetry ratio and jerkiness since these features are readily influenced by trajectory shape and do not require speculation as to the exact trajectories.

Because, in idealized form, the discrete and the ongoing cyclical movements consist of a (symmetrical) bell-shape and a (symmetrical, halve of a) sinusoid, respectively, no difference in symmetry ratio between them or from 0.5 would be expected. The first and last cyclical movement, in contrast, could have symmetry ratios deviating from 0.5 (in opposite directions) due to the requirement of combining differently shaped trajectories for their acceleration and deceleration phases (i.e. bell-shape/sinusoid and sinusoid/bell-shape, respectively). With respect to jerkiness during acceleration, no difference between discrete and first cyclical movement and between the ongoing and last cyclical movements would be expected on the basis of boundary conditions. Similarly, with respect to jerkiness during deceleration, no difference between discrete and last cyclical movement and between first and ongoing cyclical movement would be expected. When comparing these theoretical predictions to the experimentally observed effects, it can be concluded that, whereas the effect of movement type on jerkiness during acceleration is consistent with predictions following from boundary conditions, the effects on symmetry ratio and jerkiness during deceleration cannot be explained on the basis of differences in boundary conditions and must have their origin elsewhere. This implies that the identified kinematical differences can be meaningfully implicated in evaluating the tenability of the three identified theoretical perspectives on the relation between discrete and cyclical movements.

The results of the present study are consistent with the conclusion of Guiard (1993), Buchanan et al. (2003) and Smits-Engelsman et al. (2002): Cyclical movements cannot be understood in terms of concatenated series of discrete movements and the oscillator theory and the two primitives theory provide more plausible perspectives. Whereas the conclusions of the aforementioned studies were based on a comparison of discrete and ongoing cyclical movements, we demonstrated that empirical grounds for rejecting the concatenation theory can also be found within the cyclical movement itself when first, ongoing and last cyclical movements are distinguished.

In principle, the oscillator theory might be able to account for the observed differences and similarities, provided that the kinematic effects of movement initiation and abortion are elaborated upon. Explicit attempts to account for the dynamics of discrete movements from an oscillator perspective were based on a dynamical system with both limit cycle and fixed point attractors (Schöner, 1990; Zaal et al., 1999). Within this modeling approach, the initiation and termination of discrete movements were understood as transitions from fixed point attractors to a limit cycle and back again. As this principle may also be used to account for the start and end of a bout of cyclical movements, one would expect to find certain kinematic resemblances between discrete movements and the first and last cyclical movements, as explained in Section 1. Such resemblances were indeed found in the data, suggesting that the idea of transitions between attractors could account for the present data.

The two primitives theory might also be able to explain the observed kinematic differences, provided again that an account is given of the fact that the first and last cyclical movements differed from the cyclical, ongoing movements. From the perspective of the two primitives theory, this could be taken as evidence that a bout of cyclical movements starts with discrete control, which is then replaced by cyclical control; likewise, a converse switch in control could be postulated to occur at the end of a bout of cyclical movements. Buchanan et al. (2003) briefly addressed the issue of combining discrete and cyclical units of action by posing the question how many cycles it takes before a movement can be considered cyclical. Their findings concerning independently initialized cycles during early practice trials as opposed to more cyclical movement in later practice trials suggest that there might be a kind of practice-induced transition from discrete to cyclical behavior within bouts of cyclical movements. Within the explicit models proposed so far under the perspective of the two primitives theory, discrete movements arise from a fixed point dynamics and cyclical movements from a limit cycle dynamics, making use of two distinct attractor landscapes for discrete and cyclical movements. This modeling approach stands in contrast to that pursued under the oscillator theory, which exploits a single attractor landscape allowing for both fixed point and limit cycle attractors—depending on the parameter setting—to account for discrete and cyclical movements, respectively. Studies within the two primitives perspective are currently not primarily focused on detailed modeling of discrete and cyclical movements themselves, but rather on the interaction between discrete and cyclical movements when superimposed upon each other (de Rugy & Sternad, 2003; Sternad et al., 2002; Sternad et al., 2000). However, in similar fashion, one could investigate whether cyclical control is preceded by discrete control and replaced by discrete control again when the movement is scheduled to end. As it stands, no theoretical account of such control switches has been developed in the literature.

In sum, the concatenation theory should be rejected as a viable possibility to relate discrete and cyclical movement, whereas the oscillator theory and the two primitives theory should be, for the moment at least, retained as possibly viable dynamical accounts of the relation between discrete and cyclical movements. Note that the present data were obtained from reaching movements and that our findings do not necessarily generalize to aiming. In principle, the models currently available within the oscillator and the two primitives theories might be able to account for the present results, although a direct comparison between empirical and simulated data is not yet possible, because neither of the extant models was developed with the specific aim to account for the features highlighted in the present study. However, it is probably possible to incorporate transitions, be it within or between attractor landscapes, within both theories. Such an expansion of the range in which a model is able to function appropriately seems to be a legitimate endeavor, as long as it does not boil down to merely adding parameters and variables. In any case, the distinction of first, ongoing and last cycles within cyclical movement appears to be important to address when seeking to deepen our understanding of the relation between discrete and cyclical movements.

References

Beek, P. J., & Beek, W. J. (1988). Tools for constructing dynamical models of cyclical movement. *Human Movement Science, 7*, 301–342.

Beek, P. J., Peper, C. E., & Stegeman, D. F. (1995). Dynamical models of movement coordination. *Human Movement Science, 14*, 573–608.

Beek, P. J., Rikkert, W. E. I., & van Wieringen, P. C. W. (1996). Limit cycle properties of cyclical forearm movements. *Journal of Experimental Psychology: Human Perception and Performance, 22*, 1077–1093.

Beek, P. J., Schmidt, R. C., Morris, A. W., Sim, M.-Y., & Turvey, M. T. (1995). Linear and nonlinear stiffness and friction in biological cyclical movements. *Biological Cybernetics, 73*, 499–507.

Bootsma, R. J., Marteniuk, R. G., Mackenzie, C. L., & Zaal, F. T. J. M. (1994). The speed-accuracy trade-off in manual prehension: effects of movement amplitude, target size and target width on kinematic characteristics. *Experimental Brain Research, 98*, 535–541.

Bootsma, R. J., Mottet, D., & Zaal, F. T. J. M. (1998). Trajectory formation and speed-accuracy trade-off in aiming movements. *Life Sciences, 321*, 377–383.

Buchanan, J. J., Park, J. H., Young, U. R., & Shea, C. H. (2003). Discrete and cyclical units of action in a mixed target pair aiming task. *Experimental Brain Research, 150*, 473–489.

de Rugy, A., & Sternad, D. (2003). Interaction between discrete and rhythmic movements: reaction time and phase of discrete movement initiation during oscillatory movements. *Brain Research, 994*, 160–174.

Guiard, Y. (1993). On Fitts's and Hooke's laws: simple harmonic movement in upper-limb cyclical aiming. *Acta Psychologica, 82*, 139–159.

Guiard, Y. (1997). Fitts' law in the discrete vs. cyclical paradigm. *Human Movement Science, 16*, 97–131.

Haken, H., Kelso, J. A. S., & Bunz, H. (1985). Theoretical model of phase transitions in human hand movements. *Biological Cybernetics, 51*, 347–356.

Ijspeert, A., Nakanishi, J., & Schaal, S. (2003). Learning attractor landscapes for learning motor primitives. In S. Becker, S. Thrun, & K. Obermayer (Eds.). *Advances in neural information processing systems* (15).

Jakobson, L. S., & Goodale, M. A. (1991). Factors affecting higher-order movement planning: a kinematic analysis of human perception. *Experimental Brain Research, 86*(1), 199–208.

Kay, B. A., Kelso, J. A. S., & Saltzman, E. L. (1987). Steady-state and perturbed cyclical movements: a dynamical analysis. *Journal of Experimental Psychology: Human Perception and Performance, 17*, 183–197.

Kelso, J. A. S. (1981). On the oscillatory basis of movement. *Bulletin of the Psychonomic Society, 18*, 63.

Kelso, J. A. S. (1995). *Dynamic patterns: the self-organization of brain and behavior*. Cambridge, MA: MIT Press.

Latash, M. L., Scholz, J. F., Danion, F., & Schöner, G. (2002). Finger coordination during discrete and oscillatory force production tasks. *Experimental Brain Research, 146*, 419–432.

Mirkov, D. M., Milanovic, S., Ilic, D. B., & Jaric, S. (2002). Symmetry of discrete and oscillatory elbow movements: does it depend on torque that the agonist and antagonist muscle can exert?. *Motor Control, 6*, 271–281.

Morasso, P. (1986). Understanding cursive script as a trajectory formation paradigm. In H. S. R. Kao, G. P. van Galen, & H. Hoosain (Eds.), *Graphonomics* (pp. 137–167). Amsterdam: North-Holland.

Schöner, G. (1990). A dynamic theory of coordination of discrete movement. *Biological Cybernetics, 63*, 257–270.

Smits-Engelsman, B. C. M., van Galen, G. P., & Duysens, J. (2002). The breakdown of Fitts' law in rapid, reciprocal aiming movements. *Experimental Brain Research, 145*, 222–230.

Sternad, D., de Rugy, A., Pataky, T., & Dean, W. J. (2002). Interaction of discrete and rhythmic movements over a wide range of periods. *Experimental Brain Research, 147*, 162–174.

Sternad, D., & Dean, W. J. (2003). Rhythmic and discrete elements in multi-joint coordination. *Brain Research, 989*, 152–171.

Sternad, D., Dean, W. J., & Schaal, S. (2000). Interaction of cyclical and discrete pattern generators in single-joint movements. *Human Movement Science, 19*, 627–664.

Viviani, P. (1986). Do units of action really exist?. *Experimental Brain Research, 15*, 201–216.

von Holst, E. (1973). *The behavioral physiology of animal and man: the collected papers of Erich von Holst (vol. 1)*. London: Methuen.

Wei, K., Wertman, G., & Sternad, D. (2003). Interactions between rhythmic and discrete components in a bimanual task. *Motor Control, 7*, 134–154.

Woodworth, R. S. (1899). The accuracy of voluntary movement. *Psychological Review, 3*, 1–114.

Zaal, F. T. J. M., Bootsma, R. J., & van Wieringen, P. C. W. (1999). Dynamics of reaching for stationary and moving targets: data and model. *Journal of Experimental Psychology: Human Perception and Performance, 25*, 149–161.