

The point of no return in planar hand movements: an indication of the existence of high level motion primitives

Ronen Sosnik · Moshe Shemesh · Moshe Abeles

Received: 3 July 2007 / Accepted: 13 August 2007
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Abstract Previous psychophysical studies have sought to determine whether the processes of movement engagement and termination are dissociable, whether stopping an action is a generic process, and whether there is a point in time in which the generation of a planned action is inevitable (“point of no return”). It is not clear yet, however, whether the action of stopping is merely a manifestation of low level, dynamic constraints, or whether it is also subject to a high level, kinematic plan. In the present study, stopping performance was studied while nine subjects, who generated free scribbling movements looking for the location of an invisible circular target, were requested unexpectedly to impede movement. Temporal analysis of the data shows that in 87% of the movements subsequent to the ‘stop’ cue, the tangential motion velocity profile was not a decelerating function of the time but rather exhibited a complex pattern comprised of one or more velocity peaks, implying an unstoppable motion element. Furthermore, geometrical analysis shows that the figural properties of the path generated after the ‘stop’ cue were part of a repetitive geometrical pattern and that the probability of completing a pattern after the ‘stop’ cue was correlated with the relative advance in the geometrical plan rather than the amount of time that had elapsed from the pattern initiation. Altogether, these findings suggest that the “point of no return” phenomenon in humans may also reflect a high level kinematic plan and could serve as a new operative definition of motion primitives.

Keywords Motion primitives · Point of no return · Motor control · Scribbling movements

Introduction

The ability to suppress an undesired response or to abruptly bring to an end an ongoing action has a major impact on practically every aspect of our daily lives. The importance of refraining from uttering an unwise comment or instantly putting an end to a dangerous action cannot be underestimated and for this reason the act of movement inhibition and termination has been the subject of many, psychophysical, imaging and electrophysiological studies. It is not known, however, whether the stopping process, apparently a simple generic procedure which puts an action to an end, is a process which is always carried out in the same manner or whether it is planned and performed differently depending on the specific task constraints and involving different neural substrates.

The stop paradigm suggested by Logan (Logan and Cowan 1984; Logan 1994), was extensively exploited over the last 20 years as a means of measuring inhibition of a prepotent response, and was used in various ERP (De Jong et al. 1990; Bekker et al. 2005; Van Boxtel et al. 2001), imaging (Menon et al. 2001; Aaron et al. 2003; Rubia et al. 2003, 2005), and surface EMG studies (McGarry et al. 2003; Van Boxtel and Band 2000) as a tool to tease out the neural correlates mediating successful and unsuccessful inhibitory actions. The behavioral task consists of two types of trials: ‘go’ trials and ‘stop’ trials. In the ‘go’ trials, subjects perform a visual choice reaction time task (responding to a ‘go’ signal as quickly as possible). In the ‘stop’ trials, subjects are instructed to withhold their response when a ‘stop’ stimulus follows the ‘go’ stimulus.

R. Sosnik (✉) · M. Shemesh · M. Abeles
The Gonda Brain Research Center, Bar Ilan University, Ramat
Gan 52900, Israel
e-mail: ronens@mail.biu.ac.il

In order to avoid unwanted strategies that could increase the probability of successful inhibits (such as delaying the response to the ‘go’ signal), the ‘go’ trials outnumber the ‘stop’ trials.

The ease with which one can withhold a response depends on the time interval between the ‘go’ and the ‘stop’ signals, known as the ‘stop’ signal delay (SSD). The longer the SSD, the more difficult it is for one to stop and vice versa. The time needed for the ‘stop’ signal to be processed so that a response can be withheld is commonly referred to as the SSRT (Stop Serial Reaction Time). There are two versions to the stop paradigm, both aiming at estimating the latency of the response inhibition process: the constant SSD and the continuous SSD (tracking mechanism) (Logan 1994; Osman et al. 1986). In the constant SSD, subjects are tested on their ability to withhold their response while the stop signals are presented at a few different, well-spaced SSD. The estimation of the SSRT is based on the subject’s probability of inhibiting responses to the stop signal and the distribution of RT in the go trials. In the continuous SSD task, subjects are tested on their ability to withhold a response in an initial arbitrary SSD (usually 200 ms), and the percentages of the responses successfully withheld are computed. The SSD is increased (i.e., longer time interval between the go and stop signs) if the inhibition success rate is higher than 50%, and vice versa until a percent rate of 50% is achieved. A “critical” SSD can be computed that presents the time delay required for the subject to succeed in withholding a response in the stop trials half of the time (Levitt 1970; Li et al. 2005). The SSRT is then estimated by subtracting the “critical” SSD from the average RT of the go trials.

It was found that the SSRT in healthy mature individuals (Logan and Cowan 1984; Mirabella et al. 2006) and monkeys (Walton and Gandhi 2006) ranges between 200 and 300 ms and is thought to be indicative of an internal mechanism underlying the stopping process. Auditory SSRT was found to be faster than visual SSRT and the modality effect was larger when the auditory stop signal was more intense (SSRT of 187 ms when the ‘stop’ cue was a 80 db tone) (Van der Schoot et al. 2005). The SSRT index has been widely used to describe the deterioration in stopping performance with age (Williams et al. 1999) and deficiencies of response inhibition in people with neurological (Aaron et al. 2003; Rieger et al. 2003; Stewart and Tannock 1999) and psychiatric conditions (Armstrong and Munoz 2003; Rubia et al. 1998; Oosterlaan and Sergeant 1996). Furthermore, the SSRT index was found to be a valuable tool in diagnosing different types of the AD/HD disorder and assessing the effect of Methylphenidate (MPH) on AD/HD patients (Tannock et al. 1989; Schachar et al. 2000; Chhabildas et al. 2001; Scheres et al. 2003).

In order to test whether inhibiting a planned action engages the same mechanisms as stopping an ongoing action, the inhibiting performance in the ‘stop’ signal task was compared to the performances in experimental paradigms in which the instruction to stop was presented during response execution (as opposed to the ‘stop’ task in which the instruction to stop was presented *before* response execution started), such as a cursor following task (tracking a moving target with a mouse cursor, Morein-Zamir et al. 2004), circle tracing task (Bachorowski and Newman 1985, 1990) or speech production (stopping ongoing vocal production, Ladefoged et al. 1973). Although the stopping performance in these tasks, as reflected by the SSRT’s, was not different from performance in the ‘stop’ paradigm, additional analyses indicated that the performances in the stopping paradigm and cursor following task were dissociable (Morein-Zamir et al. 2004). Moreover, recent works (Scheres et al. 2003, 2004) showed that boys with ADHD demonstrated a deficit in stopping of an ongoing response (on the circle tracing task) but not in inhibition of a prepotent response and that the effect of MPH treatment on the stopping performance in the different tasks was not similar, implying that there are several stopping processes, subserved by different neural mechanisms. Hence, although the invariant SSRT may be informative as to a common basic stopping mechanism, there may be intricacies in the mediation of different, specific, stopping processes.

The increased difficulty to inhibit the response in the ‘stop’ task when the SSD is increased (Logan and Cowan 1984; Logan 1994) led to the notion that there is a time point in the control process beyond which the intended action must be produced, i.e., that there is a temporal boundary between controlled and ballistic processes in response preparation—a “point-of-no-return.” There is currently a debate, however, when and where in the information-processing system it resides. In order to answer these questions, several surface EMG and ERP studies have been conducted while subjects performed the ‘stop’ paradigm (De Jong et al. 1990, 1995) or trained on an elbow extension task in which a ‘stop’ signal, presented on random trials at various times, instructed the countermanding of that action (McGarry and Franks 1997, 2000). Whereas some of the studies suggest that the point-of-no-return lies upstream of motoneuron discharge and that inhibition is exerted *before* the spinal cord (Band and van Boxtel 1999; Van Boxtel and Band 2000), others have argued that it is a phantom, i.e., that there is no point in time which marks the onset of an involuntary process and that an earlier intended action can be inhibited right up to the point of muscle excitation (provided that there is sufficient time within which the stopping processes can act) (Osman et al. 1990; McGarry and Franks 1997, 2000; McGarry et al. 2000). It might be that the different

conclusions result from the different experimental paradigms. Whereas the ‘stop’ paradigm requested the participants to generate a response or withhold it and thus the deduction on the mechanisms of the withholding process was not based on an overt action, the flexion task called for the generation of two, counteracting actions.

Assuming that the point-of-no-return is not a phantom, it is not known whether it is merely a manifestation of execution process constraints such as the inability to swiftly impede muscle activity (low level), or whether it is also subject to the planning process constraints such as the completion of a kinematic plan (high level). Answering this question may be facilitated by conducting experiments which enable the monitoring of overt motor performance, i.e., testing the kinematics or dynamics of the movement before and after a ‘stop’ signal is presented. Although several works have measured the termination of an action after it was already underway (Morein-Zamir 2003; Morein-Zamir et al. 2004; Bachorowski and Newman 1985, 1990), the findings were dictated by the task constraints. In the cursor following task (Morein-Zamir 2003; Morein-Zamir et al. 2004) both the path and the velocity profile of the hand movement were dictated by the position and velocity of the cursor that was projected on the computer, and thus, stopping performance (i.e., the path traveled by the hand and the amount of time taken to reach a full stop) reflected the hand velocity at the time of the ‘stop’ cue. In the circle tracing task (Bachorowski and Newman 1985, 1990), no constraint was imposed on the temporal profile of the movement but the shape of the path was predefined. Furthermore, no comparative analysis of the temporal or spatial trajectories generated before and after the ‘stop’ cue was carried out. Such an analysis may be informative since it might reveal spatial or temporal motion elements which repeat themselves and cannot be stopped when a specific amount of time has elapsed or when the hand has covered a certain length of the path. These unstoppable, indivisible motion elements must run to completion once started; hence, a ‘stop’ cue presented during their generation would not result in a prompt deceleration but rather in their completion.

In the current study we aimed at testing whether the action of stopping is merely a manifestation of low level, dynamic constraints, or whether it is also subject to a high level, kinematic plan which cannot be stopped. To that end, we conducted an experiment in which human subjects were asked to move their hand freely in the workspace while holding a two-link manipulandum, and were told that each time they hit an invisible target they would hear an auditory cue (a short beep), and get a bonus (an additional small amount of money). After allowing the participants to familiarize themselves with the experimental paradigm, they were asked to train on the same task with the

additional instruction to stop moving as rapidly as possible when hearing the auditory cue (i.e., hitting a target). No constraints were imposed on the shape of path or the temporal characteristics of the movement. A lack of correlation between the hand velocity at the time of the ‘stop’ cue and the time or distance traveled by the hand up to the final stop would imply that the stopping performance is not a manifestation of a low level, dynamic (muscular) constraints. The existence of repetitive geometrical patterns in the scribbling movements that have the properties of increased probability to run to completion when the ‘stop’ cue occurs relatively late in the generation of the geometrical plan would suggest that the point-of-no-return is tied to high level, geometrical aspects of the movement. Furthermore, if a motion primitive can be defined as a basic element which cannot be broken up into simpler motion elements and, once started, must be completed, a ‘stop’ cue presented at random times throughout the task generation would enable its detection and give us a glimpse into the covert internal representation of the planned movement.

Materials and methods

Behavioral data

Nine healthy right-handed individuals (six males and three females aged 22–26 years) participated in the study. Participants were trained for ten blocks, 1 min each, spaced 2 min apart. Participants trained in a sitting position and controlled the position of a cursor with a horizontal 2-jointed low-friction manipulandum (the same setup was used in monkeys). The cursor and workspace were projected on a horizontal board at chest level in front of the subjects so that the hand position was mapped directly onto the cursor position (denoted by a green, 2 mm diameter circle). In order to prevent the participants from seeing their hand and to allow the projected light to be reflected from the board, a plain white paper was put on the table. The digital data, sampled at 100 Hz, were streamed to a computer disk for off-line analysis. Since the sampling times of the manipulandum was subject to digital noise and in order to remove the high frequency, small jerky movements caused by physiological tremor, we smoothed the data with a Gaussian filter, at a cut off frequency of 8 Hz.

The basic behavioral task was to move freely while holding the manipulandum with the dominant hand upon hearing a “GO” auditory cue, and to stop moving when a “STOP” auditory cue was heard (after 1 min). The participants were informed that each time an invisible target was hit, a short beep would be heard and a bonus—a small amount of money, would be added to the total amount of money received at the end of the last training block, hence,

motivating them to move the hand and look for the invisible targets.

The invisible target was a 20 mm diameter circle which was placed at a position, randomly selected out of 23 positions (Fig. 1). The location of the invisible target was randomly changed every time it was hit by the participant. If a target was not hit within 5 s, its position changed randomly to a new location. The participants were given no information about the spatial or temporal characteristics of target appearance.

After allowing participants to get acquainted with the task and acquire a stereotypical motion planning strategy we tested whether a velocity profile which followed an unpredictable ‘stop’ cue would have temporal characteristics different from a simple, decelerative profile (implying the existence of a point-of-no-return and unstopable motion element). To that end, we asked the nine subjects, at the end of the last training block, to train for 10 blocks on a basic “go–stop” paradigm. As in the training condition, the participants were instructed to start moving freely upon hearing the “GO” command and were told that each time a short beep was heard, a target had been hit and an extra small amount of money would be added to the total accumulated sum. However, in the “go–stop” paradigm, the participants were also asked to stop moving immediately upon hearing the beep (denoted as the ‘stop’ cue) and were instructed to wait for the next “GO” signal (which was presented 2 s after participants stopped moving). The participants were told that late hits while stopping would not count.

The late paradigm, although motivating the participants to move their hand and look for as many targets as possible, may not assure full compliance with the stopping cue. In order to verify that the results obtained in the ‘go–stop’ paradigm are the outcome of a truly stopping effort we

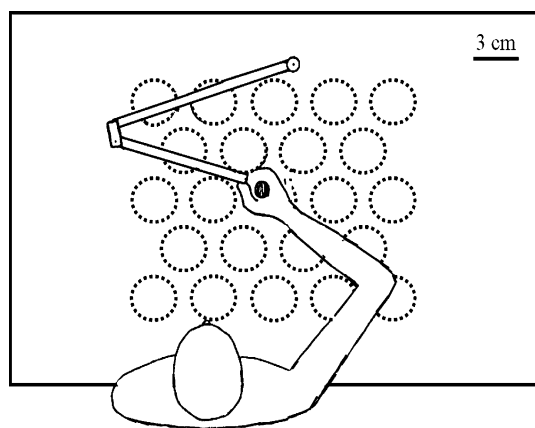


Fig. 1 Experimental setup. The participant held a two joint link manipulandum and moved freely while looking for the location of an invisible target. The dashed circles denote the possible locations of the invisible target

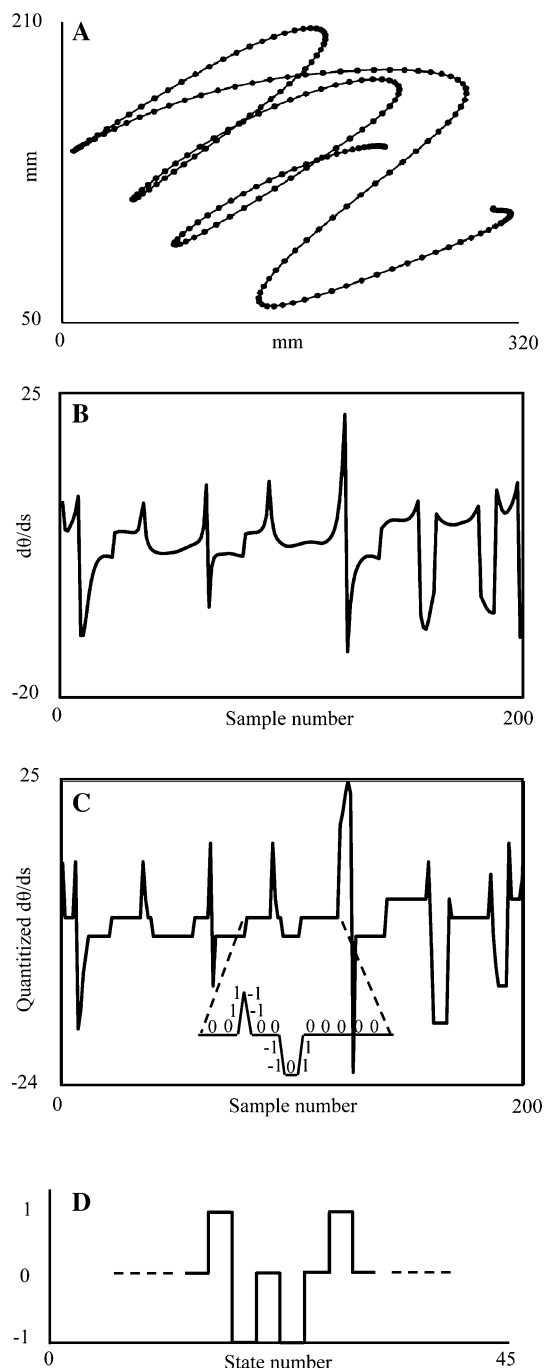
repeated the ‘go–stop’ experiment on four naïve participants and told them that they would be awarded according to their stopping performance (stopping time); i.e., a short stopping time would reward more than a long stopping time. Moreover, the stopping time was projected on the board by the end of each trial to allow the participants assess their performance and further encourage them to reduce stopping time. This stopping paradigm was termed the ‘motivational go–stop paradigm.’

The duration between the first time the tangential velocity exceeded 1 cm/s and the time at which the tangential velocity fell below 1 cm/s was termed a *trial*. A local velocity peak was counted only if its amplitude was higher from the preceding and following velocity trough by at least 15% of V_{max} (the highest velocity in the trial). Hence, velocity peaks resulting from possible noise or from small corrective movements at the end of the movement were discarded. The velocity profiles and the paths, which were generated before and after the ‘STOP’ cue were temporally and spatially analyzed.

Geometrical patterns detecting procedure

To study whether the participants’ scribbling movements were composed of repetitive geometrical patterns and whether a ‘stop’ cue presented throughout their generation would result in their completion, the following procedure was used:

- (a) Assuming that three hand positions A, B, and C were sampled consecutively in time, the Euclidian distance \overline{AB} may be different from the Euclidian distance \overline{BC} due to different motion velocities; hence, consecutively sampled hand positions may be unequally spaced (Fig. 2A). In order to inspect only the movement geometry and to eliminate the temporal characteristics of the movement we computed the path angle at each time bin (θ). We later computed $d\theta/ds$, where s is the Euclidian distance between two positions, sampled at consecutive time bins (Fig. 2B).
- (b) In order to group similar path shapes and to reduce physiological tremor noise we quantized the “analog” $d\theta/ds$ data into 16 (for four participants) or 17 (for two participants) discrete “digital” levels. So as to avoid level jittering due to small fluctuations near the levels, we used hysteresis with an upper boundary and lower boundary of $\pm 0.2 \cdot \text{level}$. We denoted an increase, decrease or no change in the change of the angle by +1, -1, and 0, respectively (Fig. 2C). Initial analysis showed that if we quantized the $d\theta/ds$ index into more than 16 levels (for four participants) or 17 levels (for two participants),



hence letting the noise/variability have greater effect, the number of detected repetitive patterns decreased significantly, as each movement was different from the other. Furthermore, when quantizing the data to large number of levels the automatically detected patterns did not match those that seemed to repeat by visual inspection. We thus chose to quantize the $d\theta/ds$ index into the highest number of levels in which repeating patterns (which can be readily seen by the naked eye) were found.

Fig. 2 The detection of a repetitive geometric pattern in a trial example. **(A)** As the instantaneous motion velocity changed throughout training, the distance between two positions, sampled consecutively in time, was not constant. The black dots depict the positions in the path in which the positions were sampled. **(B)** In order to eliminate temporal characteristics and to compensate for different motion velocities, the change in the path angle per path unit (normalized angle index) ($d\theta/ds$) was computed for each time bin (10 ms). **(C)** In order to group path segments with similar shapes, the normalized angle index was quantized into 16 levels, ranging from -24 to $+25$. (*Inset*) Zoom on sample number 74–110. The numbers $+1$, -1 , and 0 denote an increase, decrease or no change, respectively, in two consecutive $d\theta/ds$ values. **(D)** In order to obtain a size-insensitive measure of the path shape (including reduction or expansion in only one dimension), similar consecutive values were reduced to a single

- (c) So as to obtain a robust, shape–size insensitive measure of the path geometry, we reduced identical consecutive values into a single value (Fig. 2D). Each value, being different from the preceding value and the following value, was termed a “geometrical state.”
- (d) We looked for trials in which a pattern (a sequence of geometrical states) was found to repeat itself consecutively in time up to the occurrence of the ‘stop’ cue and tested whether it would be completed after the ‘stop’ cue (e.g., $[-1, 1, 0, 1, 0]$; $[-1, 1, 0, 1, 0]$; $[-1, 1, 0, \text{stop_cue}]$). This was done by testing whether the corresponding states in the sequence are the same throughout different repetitions, i.e., whether: $\sum_{i=1}^k \text{SD}(\text{stage}_{\text{repetition-1},i}, \text{stage}_{\text{repetition-2},i}, \dots, \text{stage}_{\text{repetition-}n},i) = 0$, where k is the number of states in the pattern and n is the number of times a pattern repeated itself up to the occurrence of the ‘stop’ cue. We detected patterns which started at different states and had different complexities (i.e., number of states) while aiming at detecting the longest repetitive pattern, i.e., if a pattern of five states perfectly repeated itself and was embedded in a pattern of eight perfectly repeating states, the latter pattern would be considered for further analysis. We next tested whether it would be completed after the onset of the ‘stop’ cue. Hence, the sequence “... CBCABABCABABCA-stop_cue” would be considered as a pattern composed of five states—“BCABA,” which fully repeats itself two times before the ‘stop’ cue and continues to repeat itself for three states up to the occurrence of the ‘stop’ cue—“... BCABA-BCABA-BCA-stop_cue.” The sequence would not be regarded as a two times repeating “BABCA” pattern—“... BABCA-BABCA-stop_cue” since the pattern ends just before the occurrence of the ‘stop’ cue. We denoted the detected sequences as *geometrical patterns*.

Results

Training condition

In order to familiarize the participants with the task and enable them to converge on a motion planning strategy, we asked the participants to train on the basic scribbling task for 10 training blocks (see ‘‘Materials and methods’’). A qualitative inspection of the shape of paths, generated by the participants, showed that some participants did not change their motion planning strategy throughout training and generated curved paths (e.g., Fig. 3, participant # 6, 8), whereas others shifted from generating curved movements to generating back and forth scanning movements (e.g.,

Fig. 3, participant # 1, 5), and vice versa (e.g., Fig. 3, participant # 2). One participant (# 9) generated back and forth scanning movements but the amplitude of each movement was relatively small and occupied only a small fraction of the working area.

‘‘Go–stop’’ paradigm

Temporal analysis

After the participants were well acquainted with the scribbling task, we tested whether a ‘stop’ cue presented at an apparently random time during the block (when

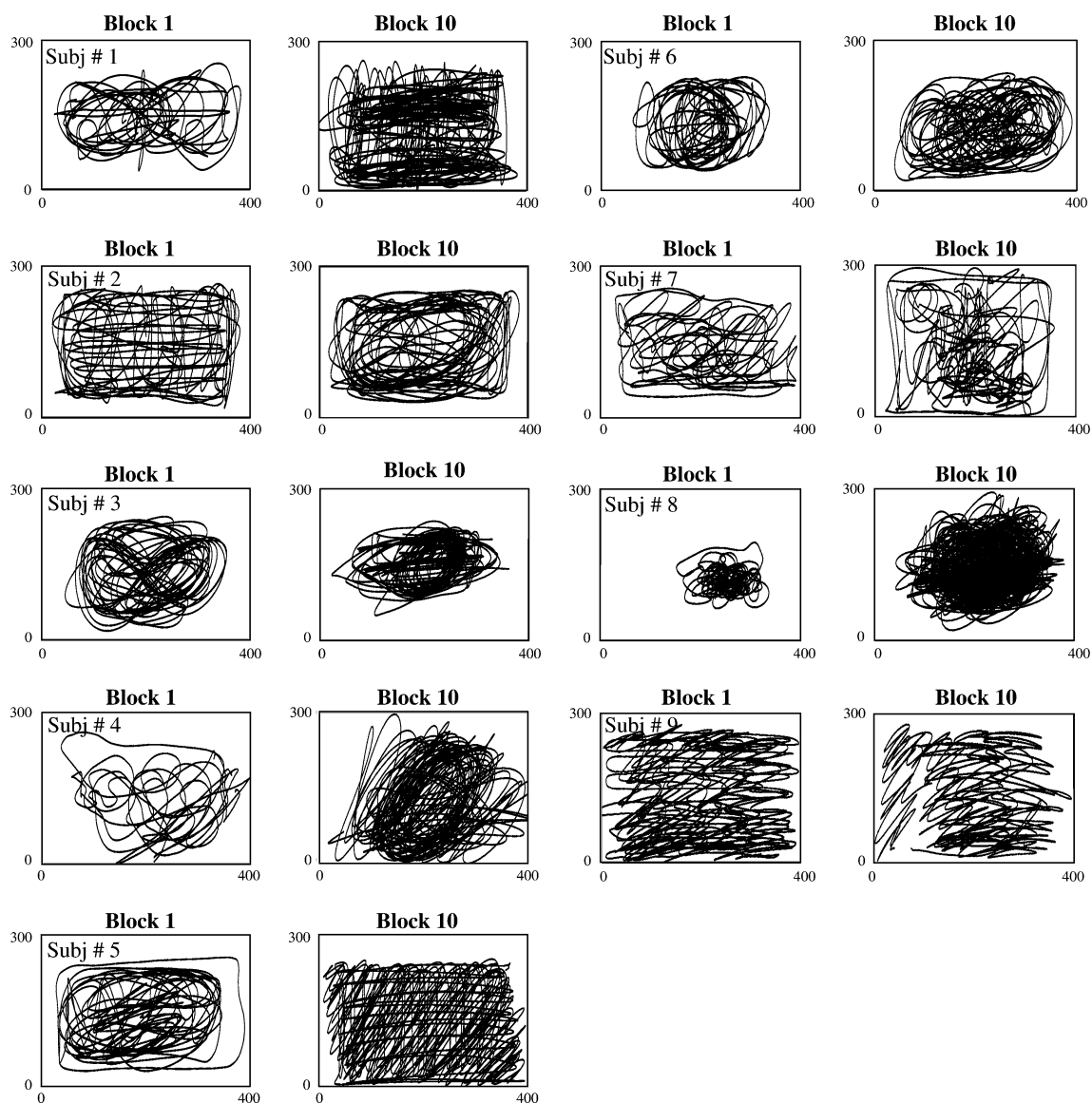


Fig. 3 The generated paths. For each participant, the left and right panels depict the paths generated in the first and last training blocks, respectively

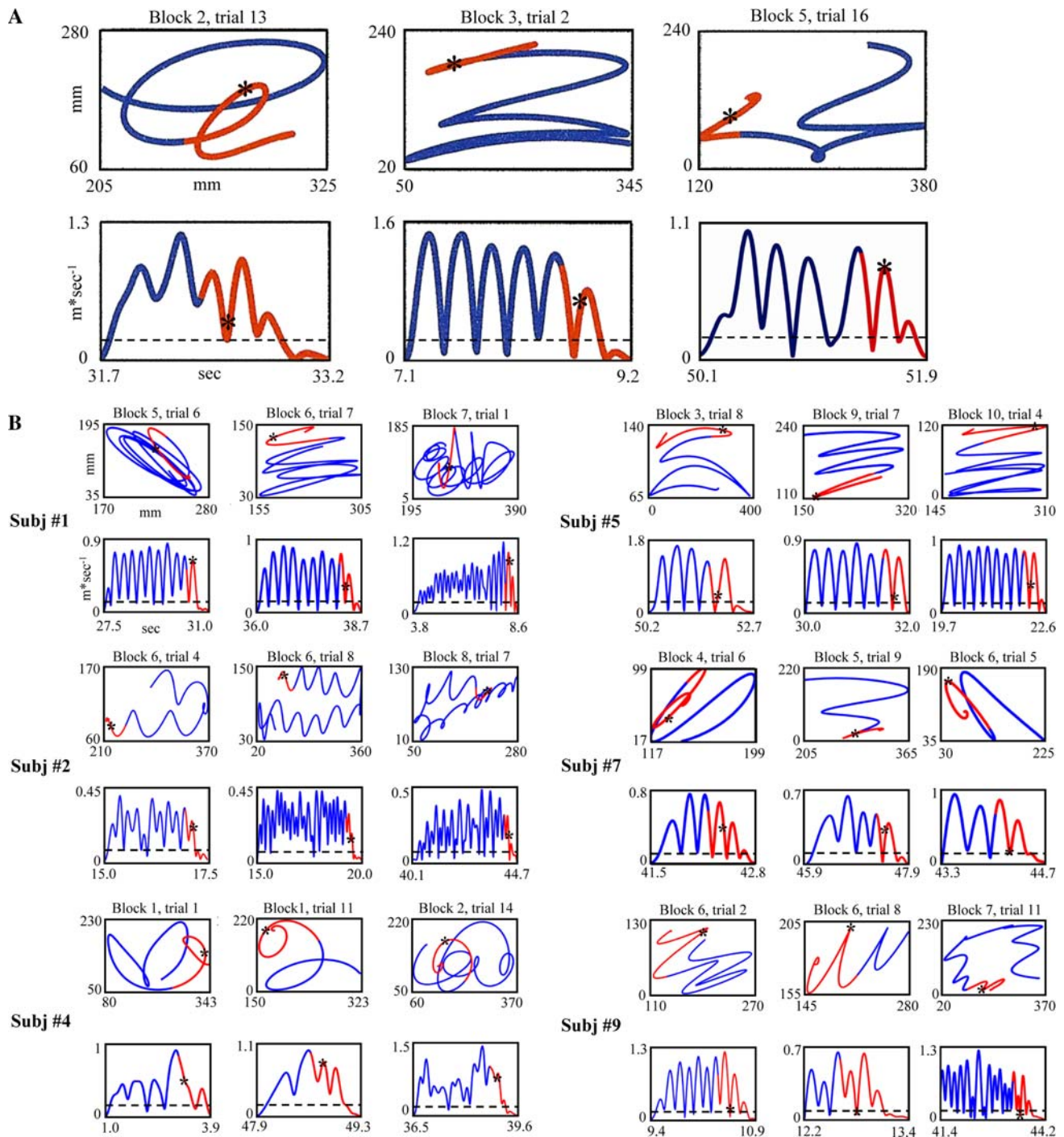


Fig. 4 The velocity profile following the ‘stop’ cue often exhibited additional peaks. (A) Three trials of one representative participant. *Upper plots*—paths. *Lower plots*—velocity profiles. The blue curve and red curve depict path (or velocity profile) generated before and after the ‘stop’ cue, respectively. The black asterisk marked on the

participants hit an invisible target) would result in a temporal or spatial pattern suggestive of a point-of-no-return. Surprisingly, an inspection of the velocity profile showed that for six participants (out of nine) the ‘stop’ cue did not result in a prompt deceleration in velocity but rather was

velocity profile and the path denotes the velocity and the position on the path, respectively, at time point: ‘stop’ cue + 200 ms. The dashed line marked on the velocity profiles denotes the peak threshold ($0.15 \cdot V_{max}$). (B) Three representative examples from six participants

followed by one or more velocity peaks. Figure 4A depicts three paths and their corresponding velocity profile, generated by one representative participant (#4) in the “go–stop” paradigm, starting from the ‘go’ signal and ending when the participant stopped moving. The ‘stop’ cue was

followed by one (Fig. 4A left plot) or two (Fig. 4A middle plot and right plot) velocity peaks. Only velocity peaks which followed a trough (a local minimum velocity) were counted; i.e., if a ‘stop’ cue occurred while the participant was accelerating (before the velocity peak), the subsequent velocity peak was not counted and only the velocity peaks taking place after the next velocity trough were counted. Eighty-three percent of the velocity profiles generated by this participant exhibited one or more velocity peak after the occurrence of the ‘stop’ cue. In order to verify that the additional velocity peaks were a “by-product” of an unstoppable motion plan and were not generated because the ‘stop’ cue was not fully processed (due to the inherent physiological sensorimotor delay, which would result in the continuation of the planned movement), we repeated the previous computation but the reference time point from which the velocity peaks were counted was the ‘stop’ cue plus an arbitrary time delay of 200 ms. Still, in 23% of the trials, the ‘stop’ cue + 200 ms time point was followed by one or more velocity peaks. The time duration from the movement initiation to the ‘stop’ cue + 200 ms was significantly longer than the time duration from the movement initiation to the first velocity peak (2.12 ± 1.84 s vs. 0.38 ± 0.16 s, respectively, $P < 0.001$) implying that the intriguing temporal profile was not part of the initial, ballistic part of the motion. The “additional velocity peaks following the ‘stop’ cue” phenomenon was found in six participants (Fig. 4B and Table 1, respectively). The time duration from the ‘stop’ cue + 200 ms time point to the final stop was not correlated with the instantaneous tangential velocity at the ‘stop’ cue + 200 ms time point ($r^2 \leq 0.06$ for all the six participants) (Fig. 5A four upper plots and two middle plots) further suggesting that stopping performance was not dictated by muscle dynamics constraints, i.e., was not tied to an active process of movement extinguishment.

For two participants (#3 and #6) only 3% and 4%, respectively, of the trials exhibited additional velocity

Table 1 Percent of trials in which additional velocity peaks occurred after the ‘stop’ cue and ‘stop’ cue + 200 ms in the basic ‘go–stop’ trials

Participant #	Counting from the ‘stop’ cue (%)	Counting from the ‘stop’ cue + 200 ms (%)
1 ($n = 87$)	80.4	22.9
2 ($n = 61$)	40.9	11.4
4 ($n = 57$)	85.9	40.3
5 ($n = 79$)	91.1	29.1
7 ($n = 60$)	43.3	21.6
9 ($n = 119$)	94.1	53.7
3 ($n = 65$)	6.8	4.1
6 ($n = 55$)	7.2	1.8

peaks after the ‘stop’ cue and for one participant (#8), the time elapsed from the occurrence of the ‘stop’ cue to the full stop frequently exceeded 2 s, suggesting that the participant had not fully understood or complied with the task instructions. The time duration from the reference time point (‘stop’ cue + 200 ms) to the final stop for the two participants (#3 and #6) was slightly positively correlated with the instantaneous tangential velocity at the reference time point ($r^2 = 0.16$ and $r^2 = 0.17$, respectively) (Fig. 5A three lower plots) implying that their stopping performance was slightly more tied to dynamics constraints than the performance of the six participants whom velocity profile exhibited additional velocity peaks after the ‘stop’ cue.

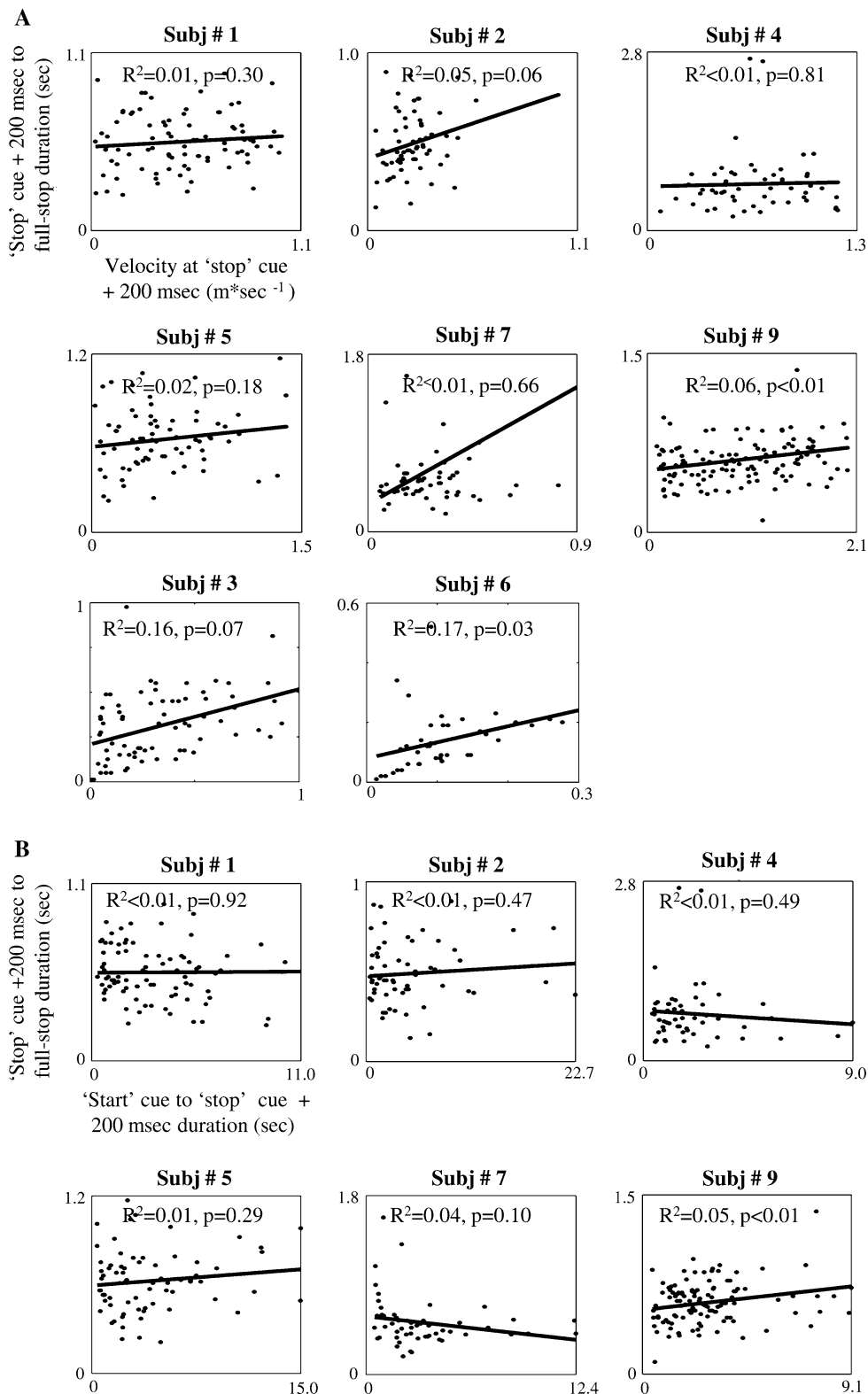
Long time interval between the ‘go’ cue and the ‘stop’ cue (Stop Signal Delay—SSD) may cause reduced attention to the ‘stop’ cue and result in a long duration to reach full stop, possibly accompanied by additional velocity peaks. We thus tested whether the findings for the six participants whom velocity profiles exhibited additional velocity peaks after the reference time point were a by-product of putative attention loss. For all six participants, no correlation was found between the SSD and the time duration taken to reach a full stop ($r^2 \leq 0.05$ for all six participants) (Fig. 5B).

Spatial analysis

We next aimed at exploring whether the extended drawing and multiple velocity peaks following a ‘stop’ cue, found in the six participants, implies the existence of geometrical motion patterns that, once started, must run to completion. We assumed that after the participants had acquired stereotypical movements in the basic training task, the geometrical motion patterns would repeat themselves throughout the ‘go–stop’ paradigm and thus could be detected. A ‘stop’ cue appearing throughout a pattern generation would result in a predictable spatial profile which completes its generation.

We detected trials in which a single spatial pattern was consecutively and accurately repeated twice or more just before the occurrence of the ‘stop’ cue and started to repeat itself once more up to the time point in which the ‘stop’ cue occurred. E.g., a pattern of eight states might consecutively repeat itself twice and then only the first six states would be generated until the state in which the ‘stop’ cue occurred (the ‘stop cue’ state). We then examined whether participants would continue generating the geometrical pattern or whether it would not run to completion. Figure 6A–D depicts four representative trials, generated by different participants, in which a single spatial pattern, composed of 10, 26, 11, and 14 states, respectively, was precisely repeated twice (Fig. 6A, B, D) or three times (Fig. 6C). In

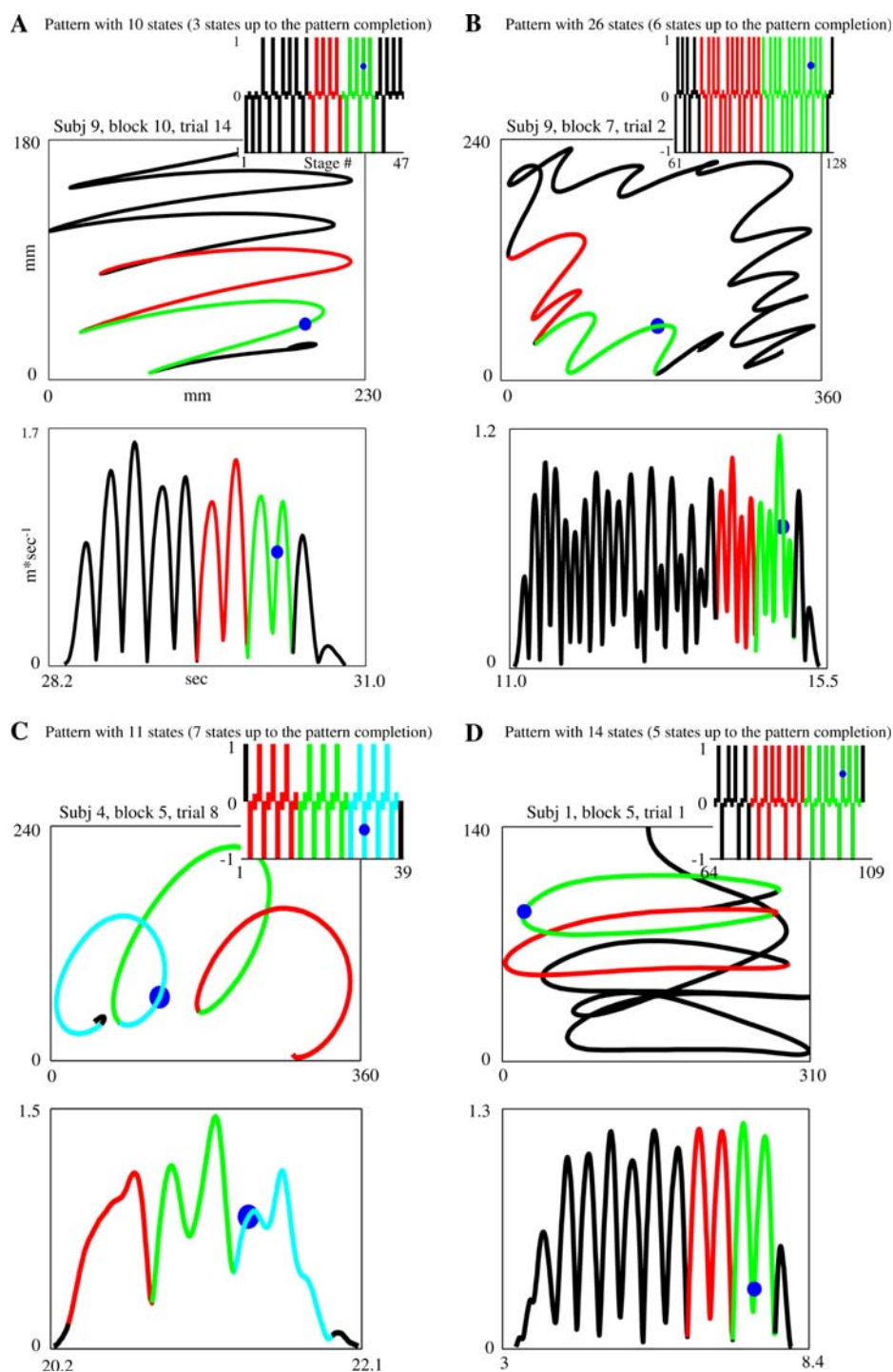
Fig. 5 The generation of additional velocity peaks after the ‘stop’ cue implies a weak dependency of the stopping performance on dynamic constraints. **(A)** Low correlation between the instantaneous tangential velocity at the time of the ‘stop’ cue + 200 ms and the time duration to stop the movement for the participants who exhibited additional velocity peaks after the ‘stop’ cue + 200 ms ($r^2 \leq 0.06$) (participant # 1, 2, 4, 5, 7, and 9) vs. higher correlation for the two participants who exhibited no additional velocity peaks after the ‘stop’ cue ($r^2 \geq 0.16$) (participant # 3 and 6). **(B)** Low correlation between the ‘go’ cue to ‘stop’ cue + 200 ms to full-stop duration for all six participants whose velocity profiles exhibited additional peaks after the ‘stop’ cue ($r^2 \leq 0.05$)



all four cases, the spatial pattern was repeated to its full extent although the ‘stop’ cue occurred at a time point in which 3, 6, 7, or 5 states, respectively, were missing to complete the pattern, suggesting that the ‘stop’ cue

occurred after the point-of-no-return. The probability that a repetitive pattern with x states, each having one value: 1, 0, or -1 with equal probability, would fully repeat itself although it was “disturbed” by a ‘stop’ cue at state y , is

Fig. 6 An indication of the existence of an unstoppable geometric motion pattern. *Upper plots*—paths. *Lower plots*—velocity profiles. *Insets*—geometric states. The first, second, and the third pattern repetition (if present) are denoted by red, green, and cyan bar/curve, respectively. The blue dot depicted in the Inset, upper plots and lower plots, denotes the state, position on the path or time point, respectively, in which the ‘stop’ cue occurred



$\frac{100}{2^{x-y}}$ % (after the ‘stop’ cue, each state, being different from the last state, can have one value out of two possible values). Hence, the probabilities for the three patterns to repeat themselves by chance for the third time after the ‘stop’ cue were only 0.7, 3.1, 12.5, and 1.5%, respectively.

In order to obtain a qualitative measure of the point-of-return phenomenon, we first computed, for each participant, the percent of trials in which a pattern repeated itself consecutively in time up to the appearance of the

‘stop’ cue. In 50% (44 out of 87), 26% (16 out of 61), 45% (26 out of 57), 40% (32 out of 79), 38% (21 out of 60), and 48% (35 out of 119) of the trials generated by participant # 1, 2, 4, 5, 7, and 9, respectively, a pattern repeated itself up to the ‘stop’ cue state. We then compared the number of trials in which the pattern continued to repeat itself *after* the ‘stop’ cue with the expected number of trials. The analysis was done on four trial groups in which an additional 1–3, 4–6, 7–9, or 10–12 states were missing to

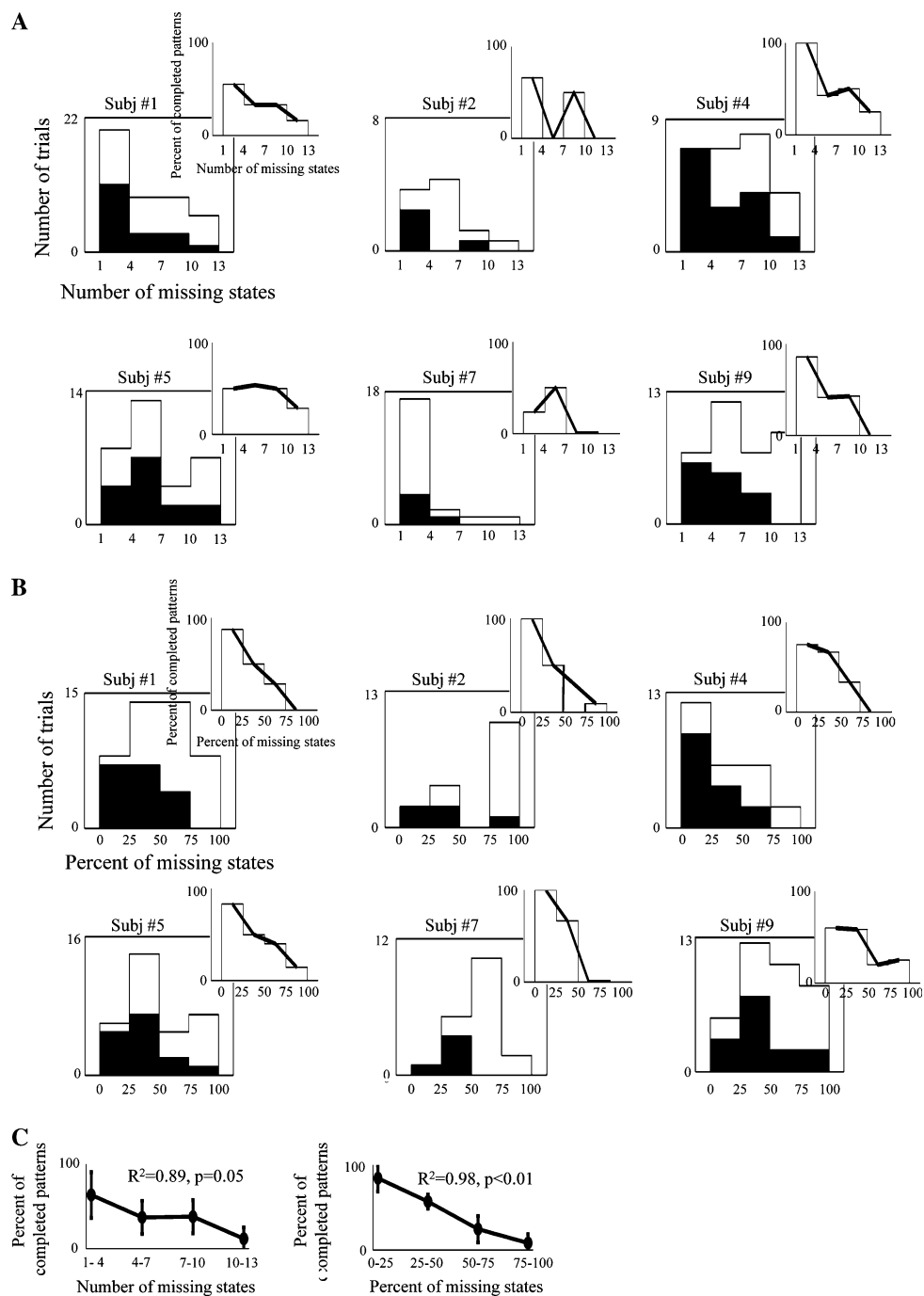


Fig. 7 The dependency of the pattern completion probability on absolute and relative ‘stop’ cue state position. **(A)** For each participant, all the trials which necessitated 1–3, 4–6, 7–9, and 10–13 states to successfully complete the pattern are grouped and their number is depicted by the height of the bar. The number of trials in which the pattern was completed is depicted by the height of the black bar. *(Inset)* The percent of trials in which the pattern was completed vs. the number of missing states. **(B)** For each participant, all the trials in which 0–25%, 25–50%, 50–75%, or 75–100% of the total pattern states that were missing to complete the pattern were grouped, and their number is depicted by the height of the bar. The number of trials in which the pattern was completed in each group is depicted by the

height of the black bar. *(Inset)* The percent of trials in which the pattern was completed vs. the relative position of the stop-cue state. The probability to complete a pattern was not correlated with the absolute number of states up to the completion of the pattern and was correlated with the position of the stop-cue state, relative to the total pattern length. **(C)** Dependency between the absolute number of missing states (left plot) or relative advance in the geometrical pattern (right plot) and the probability for finishing a pattern for the data ensemble (six participants). The probability to complete a pattern was better correlated with the relative advance than the number of missing states ($r^2 = 0.99$ vs. $r^2 = 0.85$)

Table 2 Number of trials, in which a pattern with 1–3, 4–6, 7–9, or >10 missing was completed/not completed after the ‘stop’ cue in the basic ‘go–stop’ paradigm. In each group, the completed/not completed trial numbers are the ensemble of the six participants (# 1, # 2, # 4, # 5, # 7, and # 9). No χ^2 test was performed on the third and fourth trial group as it is only valid on expected values ≥ 2

		# Completed patterns	# Uncompleted patterns	χ^2 test (DoF = 1)
1–3 states to complete the pattern	Measured	36	29	$P < 0.001$
	Expected	16.25	48.75	
4–6 states to complete the pattern	Measured	19	31	$P < 0.001$
	Expected	3.12	46.88	
7–9 states to complete the pattern	Measured	13	18	Not valid
	Expected	$\ll 1$	~ 31	
>10 states to complete the pattern	Measured	4	24	Not valid
	Expected	$\ll 1$	~ 28	

Table 3 Data of the ‘motivational go–stop’ paradigm. The leftmost column presents the percent of trials in which additional velocity peaks occurred after the ‘stop’ cue + 200 ms. The second column from the left presents the time duration from the ‘stop’ cue + 200 ms to the final stop and the correlation (presented in brackets) between

the duration and the instantaneous velocity at the time of the ‘stop’ cue + 200 ms. The second column from the right presents the percent of trials in which a geometrical pattern was found up to the ‘stop’ cue. The rightmost column presents the percent of trials in which a pattern was found to repeat itself after the ‘stop’ cue + 200 ms

Participant #	% of peaks	Time duration from the ‘stop’ cue + 200 ms to the final stop (s)	% of trials in which a geometrical pattern was found up to the ‘stop’ cue	% of trials in which a pattern was completed after the ‘stop’ cue
10 ($n = 204$)	39.70	0.41 ± 0.21 ($r^2 = 0.01$, $P < 0.13$)	15.19% (31 out of 204)	83.33% (25 out of 31)
11 ($n = 88$)	76.13	0.48 ± 0.13 ($r^2 < 0.01$, $P = 0.49$)	22.72% (20 out of 88)	50% (10 out of 20)
12 ($n = 34$)	0	0.53 ± 0.16 ($r^2 = 0.01$, $P = 0.45$)	0%	0%
13 ($n = 111$)	29.72	0.65 ± 0.26 ($r^2 = 0.01$, $P = 0.23$)	62.16% (69 out of 111)	69.56% (48 out of 69)
14 ($n = 59$)	20.33	0.47 ± 0.18 ($r^2 < 0.01$, $P = 0.49$)	40.67% (24 out of 59)	75.00% (18 out of 24)
15 ($n = 69$)	37.68	0.55 ± 0.16 ($r^2 < 0.01$, $P = 0.75$)	40.57% (28 out of 69)	53.57% (15 out of 28)

complete the pattern after the occurrence of the ‘stop’ cue (Fig. 7A). For each of the four groups the number of trials in which the states following the ‘stop’ cue matched the missing states was significantly higher than the expected number (χ^2 test, DoF = 1, $P < 0.001$) (Table 2), suggesting that the completion of the patterns was not a coincidence.

Next, we looked for a geometrical state from which the pattern must run to completion (i.e., point-of-no-return). The position of the point-of-no-return can be dependent on at least two factors. The first is that only the *absolute* number of states, required to complete the pattern after the ‘stop’ cue determines whether the subject will complete generating the pattern or promptly stop it. In this case, the probability for a pattern to be completed after the ‘stop’ cue would be negatively correlated with the number of missing states. Alternatively, the *relative* position of the ‘stop’ cue state in the whole pattern may determine the performance; e.g., if the ‘stop’ cue occurs relatively near the beginning of the pattern, e.g., at state 2 in a pattern of 10 states (e.g., after 20%), it would not run to completion whereas its appearance later in the pattern, e.g. at state 6 in a pattern of 14 states (e.g., after $\sim 40\%$), would result in its

completion. Since in both cases 8 states are needed to complete the pattern, the difference in performance would imply that the relatively advanced position in the geometrical plan up to the ‘stop’ cue determines whether the pattern will run to completion or not.

In order to examine the “absolute number of missing states” hypothesis we tested whether there was a correlation between the probability of completing a pattern and the number of states missing to complete it after the ‘stop’ cue. For all participants, no consistent dependence was found between the two variables (Fig. 7A Insets). In order to examine the “relative position of the ‘stop’ cue” hypothesis, we grouped trials in which the ratio between the number of missing states and the total number of states in the pattern was similar and tested whether the probability to finish the pattern was correlated with the relative position of the ‘stop’ cue state in the whole pattern. The analysis was done for trial groups in which 0–25, 25–50, 50–75, or 75–100% of the total number of states were missing to complete the pattern after the ‘stop’ cue (Fig. 7B). As can readily be seen, the probability to finish the pattern increased when the ‘stop’ cue state occurred relatively later in the pattern (i.e., lower

percent of missing states) (Fig. 7B Insets), supporting the hypothesis that the probability to finish the pattern is dependent on the relative position of the ‘stop’ cue in the geometrical plan. Figure 7C summarizes the absolute and relative advance analysis for the data ensemble of the six participants. The correlation between the probability to finish a pattern and the relative advance in the geometrical plan was higher than the correlation between the probability to finish a pattern and the absolute number of missing states ($r^2 = 0.99$, $P = 0.01$ vs. $r^2 = 0.85$, $P = 0.07$).

In trials in which a geometrical pattern was found to consist of the same number of states, an increase or decrease in the number of missing states to complete a pattern after the ‘stop’ cue would necessarily result in a decrease or increase, respectively, in the relative advance in the geometrical plan. In order to find the effect that the absolute number of missing stages (N) and relative advance in the geometrical plan (R) have on the probability to complete the pattern (P) we computed for each of the two independent variables, their partial correlation with the probability to complete the pattern (see Stark et al. 2006; Fisher 1925). The partial correlation of the number of missing states with the probability to complete the pattern— $r(N, P|R)$ was 0.04 ($P = 0.589$, $df = 170$) while the partial correlation of the relative advance in the geometrical plan with the probability to complete the pattern $r(R, P|N)$ was -0.50 ($P < 0.001$, $df = 170$) indicating that the probability to finish a pattern was indeed strongly dependent on the relative advance in the geometrical plan rather than on the number of missing states.

In order to test whether the dependency between the relative advance in the geometrical plan and the probability to finish the pattern was not in fact a manifestation or a by-product of a temporal relation, i.e., that the putative geometrical dependency masked a temporal dependency, we tested whether the point-of-no-return was related to the time interval between the pattern initiation and the ‘stop’ cue. We computed the start pattern to ‘stop’ cue time intervals both in the trials in which the patterns were found to repeat themselves after the ‘stop’ cue and trials in which patterns did not repeat themselves after the ‘stop’ cue. The “start_pattern_to_stop_cue” time intervals in the two trial groups were not significantly different ($P > 0.07$ for all the participants) suggesting that the point-of-no-return was not clearly related to the temporal aspects of the movement.

We examined whether the geometrical patterns that were found to consecutively repeat themselves were generated in roughly the same time durations (isochrony). Assuming that an isochrony between two or more segments suggests that the different segments are internally represented as the same segment, a high degree of isochrony between the patterns that were found by the algorithm to

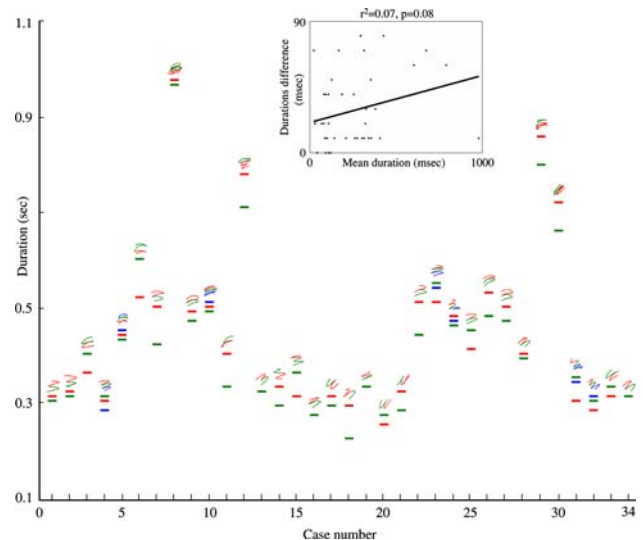


Fig. 8 Isochrony between consecutive repetitions of a geometric pattern. For each trial in which a pattern was found to consecutively repeat itself for two, or three times, the first, second, and third repetition time durations are depicted by red, green, and blue lines. The red, green, and blue curves depict the paths generated in the first, second, and third (if present) pattern repetitions. The data are taken from a representative participant (# 9). In some cases (# 13 and # 19), there was an exact isochrony between the durations of the first, second, or third pattern generation and thus only one time duration (for cases with two repetitions) or two time durations (for cases with three repetitions) are depicted. (Inset) The mean of the two (or three) pattern repetition durations was not correlated with the amount of isochrony between the durations (the time difference between the durations) ($r^2 = 0.07$, $P = 0.08$)

repeat themselves may suggest that the patterns were indeed regarded as the same motion entity. Figure 8 depicts the time durations of the first, second, and third (if present) repetition of the patterns generated by one representative participant (# 9) in different trials throughout the “go-stop” paradigm, and the generated patterns. As can readily be seen, there was a high degree of isochrony between the time durations of the generations of the geometrical patterns that were found to consecutively repeat themselves within a trial. The extent of similarity between the time durations ranged from complete isochrony (e.g., cases # 13, # 16, and # 19) to two cases in which the difference in the time durations reached 80 ms (e.g., case # 6 and # 7). The mean + SD time difference for all the cases in which a repetitive pattern was found was 28 ± 24 ms, suggesting that the geometrical entities were indeed generated in roughly the same time durations. Similar results were found for the other five participants: participant # 1, 2, 4, 5, and 7 (35 ± 27 , 43 ± 35 , 22 ± 13 , 37 ± 19 , and 25 ± 22 ms, respectively). There was no correlation between the degree of isochrony and the mean duration that was taken to generate the pattern (Inset, $r^2 = 0.07$, $P = 0.08$ for all the participants), i.e., the high degree of

isochrony was not an epiphenomenon of the short time that was taken generate the pattern.

No repetitive patterns or points-of-no-returns were found in the scribbling movements of the two participants for which no velocity peaks were found after the ‘stop’ cue (participant # 3 and # 6) or the participant who did not comply with the task instructions (participant # 8). In only 5% and 4% of the trials generated by participant # 3, # 6, respectively repetitive patterns were found up to the occurrence of the ‘stop’ cue and in none of them the patterns were completed after the ‘stop’ cue.

In order to test the possibility that the temporal and spatial patterns were caused by lack of a real effort to promptly put to an end an ongoing motion, we asked six naïve participants to train on the same paradigm but rewarded them according to their stopping performance (i.e., time duration from the ‘stop’ cue to the final stop). The temporal analysis showed that five participants (out of six) generated additional velocity peaks after the ‘stop’ cue + 200 ms and the time duration from the ‘stop’ cue + 200 ms to the final stop was not correlated with the instantaneous velocity at the time of the ‘stop’ cue + 200 ms ($P \leq 0.01$) (Table 3 two leftmost columns). These results are not qualitatively different from the results obtained in the basic ‘start–stop’ paradigm. Furthermore, as in the results obtained in the basic ‘start–stop’ paradigm, the spatial analysis has shown that for the five participants whom velocity profiles exhibited additional velocity peaks after the ‘stop’ cue, repetitive spatial patterns were found and the patterns were frequently completed although the ‘stop’ cue occurred throughout their generation (Table 3 two rightmost columns and Fig. 9). Overall, these results suggest that the results obtained in the basic ‘go–stop’ paradigm were not a product of low motivation to put the ongoing movement to an end.

Discussion

We tested whether the point-of-no-return, previously suggested to reflect low level dynamic constraints, is also affected by high level features, such as the existence of a kinematic plan. In order to test the “high level” constraints hypothesis we used a new experimental paradigm in which the stopping performance was tested while the hand was already in motion. Several works have used experimental paradigms in which the stop cue was presented *after* the movement has started, such as the circle tracing task (Bachorowski and Newman 1985, 1990), or the cursor following task (Morein-Zamir 2003; Morein-Zamir et al. 2004); however, in these tasks, the path or both the path and the velocity profile were predefined. Such paradigms, although allowing the researcher to examine whether

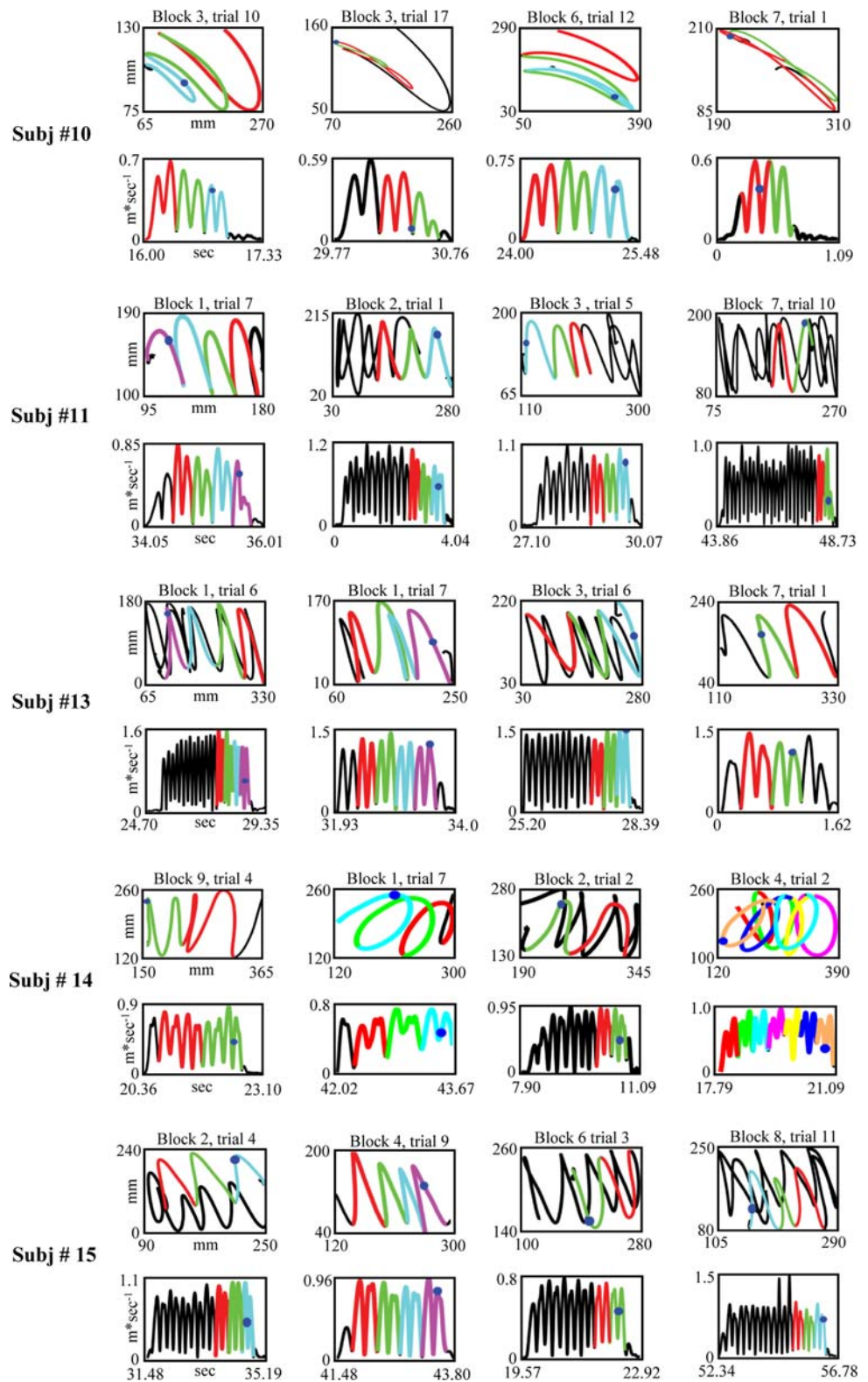
exhortation of a prepotent action and termination of an ongoing action share the same mechanism, cannot inform as to its nature. In our paradigm—the free scribbling task, no spatial or temporal constraints are imposed on the generated trajectory and thus we were able to test the existence of spatial or temporal patterns which run to completion even after the apparently random occurrence of a ‘stop’ cue, suggesting the existence of a point-of-no-return. Such basic motion patterns—primitives—may possibly run to completion after a certain amount/percent of time or path length has elapsed.

Whereas the findings from the cursor following task (Morein-Zamir 2003; Morein-Zamir et al. 2004) and the ‘stop’ paradigm (Logan and Cowan 1984) suggest that the two tasks share the same stopping mechanisms and that stopping performance is dictated by two consecutive states: a cognitive state in which the ‘stop’ cue is processed (i.e., SSRT) and a low level state, in which the action is run to completion as rapidly as possible and is tied solely to the dynamic aspects of the movement (e.g., velocity), our temporal and spatial analysis provides indication that the stopping performance is subject, at least to some extent, to high level, constraint such as a completion of a kinematic, geometrical plan. We have shown that surprising temporal patterns (additional velocity peaks after the ‘stop’ cue) are not caused by lack of attention or motivation to comply with the task instructions and that they are tied to the existence of a stereotypical repetitive geometrical shapes which are acquired throughout the initial training episode. The completion of the geometrical patterns after the occurrence of the ‘stop’ cue is not an artifact of a dynamic action such as pendulum swinging-like motion around a stopping point that resembles the previous pattern as we would expect consecutively generated patterns to have gradually decreasing sizes (the path traversed by the pendulum is gradually decreasing in each swing). As is readily seen in Fig. 6, we did not notice a gradual reduction in shape size throughout consecutive generations of a geometrical pattern, not before or after the ‘stop’ cue.

Limitations of the geometrical pattern detection method

The geometrical analysis that we applied on the data has two inherent drawbacks. Firstly, in our geometrical analysis we only incorporated patterns which accurately and consecutively repeat themselves up the ‘stop’ cue. We then assumed that the states, following the last state in the preceding pattern generation, were part of the same repetitive pattern and we tested whether the pattern would run to completion after the ‘stop’ cue. Apart from the time economy and simplicity of the algorithm which detects such patterns, a consecutively repeating pattern may

Fig. 9 Unstoppable geometric motion patterns were also detected when participants were rewarded according to their stopping performance (the ‘motivational go–stop’ paradigm). *Upper plots*—paths. *Lower plots*—velocity profiles. The first, second, third, fourth, fifth, sixth, and seventh pattern repetition (if present) are denoted by red, green, cyan, magenta, yellow, blue, and orange curve, respectively. The blue dot depicted in the upper plots and lower plots denotes the position on the path or velocity, respectively, at the time point of the ‘stop’ cue + 200 ms



represent a basic motion element. The high degree of isochrony that was found between the time durations of the different repetition generations further strengthens this notion (Fig. 8). Although the states up to the ‘stop’ cue

matched the first states of the pattern, the participant may not have planned to generate the same pattern or any other pattern at all and thus, the finding that the participant had not completed generating the pattern does not imply that a

point-of-no-return does not exist in this pattern generation or, alternatively, that it would have been manifested had the ‘stop’ cue appeared later in the pattern generation. Overall, this could have resulted in underestimating the percent of points-of-no-return. Secondly, in our statistical analysis we did not incorporate patterns which repeated themselves in a non-consecutive manner just before the ‘stop’ cue, nor did we look for cases in which a pattern repeated itself in different trials or blocks.

The shortcoming of detecting patterns which comply with the two conditions is the relatively low number of trials in which a pattern was found. Although the results reached statistical significance even though the number of cases was relatively low, finding patterns that repeat themselves on different trials or even in different blocks and incorporating them into the analysis might shift the shape of the correlation function in one direction or the other.

Since our ability to detect a point-of-no-return was based on the completion of a repetitive geometrical pattern after the occurrence of a ‘stop’ cue, we could not find an indication for the existence of such a phenomenon in the two participants for whom no repetitive geometrical pattern were found. It might be that given additional practice the two participants would acquire stereotypical spatial patterns which would serve as basic, unstoppable motion elements and thus the occurrence of a ‘stop’ cue throughout their generation would result in their completion (implying the existence of a point-of-no-return).

Possible extensions

The spatial–temporal repeatability of segments of scribbling movements appears to be a robust feature of this task. The mechanisms that might account for the “stereotyped” behaviors could be a minimization of control commands or a dynamic optimization strategy such as reduced mean torque or energy. Whatever the movement generation mechanisms may be, a point of no return was found both for the participants who generated curved movements (e.g., participant # 4) and the back-and-forth scanning participants (e.g., participant # 5) suggesting that the intriguing stopping performance was not tied to a specific motion planning strategy. Since the goal of the current work was not to characterize the movements these issues were not reported here, however, a detection of kinematic and/or dynamic feature underlying the generation of all the repetitive patterns (being candidate to serve as basic motion elements) would hopefully shed light on the characteristics of the basic elements used by the CNS to construct complex movements.

Doubts exist in the stop-signal paradigm (Logan and Cowan 1984; Logan 1994) about the involvement of active

inhibitory processes; whether this is a direct manifestation of the act of control that interrupts a response. Successful stopping may be the result of a non-response replacing a response (active process), or the discontinuation of support for finishing a response (passive process) (Band and van Boxtel 1999). In the current study, we did not record EMG activity since our aim was not to determine whether stopping an ongoing movement is a passive or active process (involving co-contractions of the muscles). However, our findings show that the completion of the geometrical pattern was occasionally characterized by a change in the movement direction which does not favor the possibility of a passive stopping process (Fig. 6D).

Previous works have shown that the individual components of a ballistic movement are relatively fixed in duration and the amount of EMG activity is altered within this time interval to produce the different forces required for fast movements of different amplitude (Hallett and Marsden 1979; Brown and Cooke 1984, 1990; Cooke et al. 1985; Cooke and Brown 1994). Both agonist and antagonist muscles remain under some feed-back control during the entire course of a ballistic movement, but the amount of influence of feed-back depends on the supraspinal command signal and the changes in the muscle spindle length during the course of the movement. This is in contrast to ongoing movements which are under continuous feed-back control of several reflex loops. These findings supported the notion that the point-of-no-return phenomenon is a manifestation of a low level, peripheral mechanisms. In our analysis in all the trials in which a pattern was found to repeat itself, the ‘stop’ cue was found to appear at least 700 ms after the initiation of the movement, thus precluding the possibility that the pattern completion phenomenon was a part of a ballistic movement. Measurement of surface EMG from some of the moving limb muscles (e.g., biceps, triceps, deltoid, and forearm muscles) and detection of several passive and active stopping action waves involved in the completion of a geometrical motion element after the ‘stop’ cue would further suggest that the stopping process is subject to high level constraints.

In the current study, we did not find a step function dependency between the relative position of the ‘stop’ cue and the probability for a pattern to fully repeat itself (Fig. 7). In other words, we were unable to pin down the exact location of the point-of-no-return. The finding that there were trials in which participants did not complete the pattern even though the ‘stop’ cue occurred relatively late in the pattern generation (hence an increased probability to finish a pattern) might result from the participants’ lack of intention to repeat the pattern another time although the states up to the ‘stop’ cue matched the ones in the previous pattern repetition generation. Alternatively, the stop manipulation, which is subject to a high level, kinematic

plan, may be mediated by a stopping mechanism that manifests probabilistic attributes. Further work is needed to unravel the characteristics of the point-of-no-return.

Summary

Overall, our results indicate that in a free scribbling task in which both the path and the velocity profile are chosen by the participants, there are individual stopping times and differences in the ability to stop during different states of the pattern generation, suggesting the existence of a point-of-no-return. Furthermore, the point-of-no-return is subject to high level constraints, a kinematic plan, and is linked to geometrical attributes of the movements rather than to temporal ones. These findings are consistent with previous studies on drawing movements (Viviani and Flash 1995; Sosnik et al. 2004, 2006) and three-dimensional reaching movements (Torres and Zipser 2002; Torres and Andersen 2006) which showed that the shape of the path traveled by the hand and its time dependent kinematic attributes (i.e., velocity, acceleration) are separately represented in the brain. Furthermore, the current findings suggest that the different representation is manifested not only in movement planning and generation but also in its termination.

We would like to stress that we do not argue that the point-of-no-return is a motion feature which exist in all the participants or even that it is a motion feature, once expressed in a subject, that will be expressed in all the participant's scribbles (as is evident from Table 2). However, the finding that some of the participants continue in most of the trials to complete the geometrical pattern after the 'stop' cue + 200 ms is a clear evidence that the point-of-no-return is not a phantom and that there are complex patterns of movement which serve as basic, elementary motion units. We believe that these findings provide new insights into the nature and mechanisms underlying motor planning and generation and hint at the tremendous versatility, sophistication and adaptability of the motor system.

Acknowledgments We would like to thank Prof. Tamar Flash and Prof. Claude Ghez for their insightful comments. This work was supported in part by the German Federal Ministry of Education and Research (BMBF) within the framework of German-Israeli Project Cooperation (DIP) and the Rich center.

References

- Aaron AR, Fletcher PC, Bullmore ET, Sahakian BJ, Robbins TW (2003) Stop-signal inhibition disrupted by damage to right inferior gyrus in humans. *Nature Neurosci* 6:115–116
- Armstrong IT, Munoz DP (2003) Inhibitory control of eye movements during oculomotor counter demanding in adults with attention-deficit hyperactivity disorder. *Exp Brain Res* 152:444–452
- Bachorowski JA, Newman J (1985) Impulsivity in adult: motor inhibition and time-interval estimation. *Pers Individ Differ* 6:133–136
- Bachorowski JA, Newman J (1990) Impulsive motor behavior: effects of personality and goal salience. *J Pers Soc Psychol* 58:512–518
- Band GPH, Van Boxtel GJM (1999) Inhibitory motor control in stop paradigms: review and reinterpretation of neural mechanisms. *Acta Psychologica* 101:179–211
- Bekker EM, Kenemans JL, Hoeksma MR, Talsma D, Verbaten MN (2005) The pure electrophysiology of stopping. *Int J Psychophysiol* 55:191–198
- Brown SH, Cooke JD (1984) Initial agonist burst duration depends on movement amplitude. *Exp Brain Res* 55:523–527
- Brown SH, Cooke JD (1990) Movement-related phasic muscle activation. I. Relations with temporal profile of movement. *J Neurophysiol* 63(3):455–464
- Chhabildas N, Pennington BF, Willcutt EG (2001) A comparison of the neurological profiles of the DSM-IV subtypes of ADHD. *J Abnorm Child Psychol* 29:529–540
- Cooke JD, Brown SH (1994) Movement-related phasic muscle activation: III. The duration of phasic agonist activity initiating movement. *Exp Brain Res* 99:473–482
- Cooke JD, Brown S, Forget R, Lamarre Y (1985) Initial agonist burst duration changes with movement amplitude in a deafferented patient. *Exp Brain Res* 55(60):184–187
- De Jong R, Coles MGH, Logan GD, Gratton G (1990) In search of the point of no return – the control of response processes. *J Exp Psychol – Human Percept Perform* 16(1):164–182
- De Jong R, Coles MGH, Logan GD (1995) Strategies and mechanisms in nonselective and selective inhibitory motor control. *J Exp Psychol – Human Percept Perform* 21:498–511
- Fisher RA (1925) *Statistical methods for research workers*. Oliver and Boyd, London
- Hallett M, Marsden CD (1979) Ballistic flexion movements of the human thumb. *J Physiol* 294:33–50
- Ladefoged P, Silverstein R, Papcun G (1973) Interruptibility of speech. *J Acoust Soc Am* 54:1105–1108
- Levitt H (1970) Transformed up-down methods in psychoacoustics. *J Acoust Soc Am* 49:467–477
- Li CSR, Krystal JH, Mathalon DH (2005) Fore-period effect and stop-signal reaction time. *Exp Brain Res* 167:305–309
- Logan GD (1994) On the ability to inhibit thought and action: a users' guide to the stop signal paradigm. In: Dagenbach D, Carr TH (eds) *Inhibitory processes in attention, memory, and language*. Academic press, San Diego, pp 189–239
- Logan GD, Cowan WB (1984) On the ability to inhibit thought and action: a theory of an act of control. *Psychol Rev* 91:295–327
- McGarry T, Franks IM (1997) A horse race between independent processes: evidence for a phantom point of no return in the preparation of a speeded motor response. *J Exp Psychol – Human Percept Perform* 23(5):1533–1542
- McGarry T, Franks IM (2000) Inhibitory motor control in stop paradigms: comment on Band and van Boxtel (1999). *Acta Psychol* 105:83–88
- McGarry T, Inglis JT, Franks IM (2000) Against a final ballistic process in the control of voluntary action: evidence using the Hoffmann reflex. *Motor Control* 4(4):469–485
- McGarry T, Chua R, Franks IM (2003) Stopping and restarting an action at various times. *Quart J Exp Psychol Sect A – Human Exp Psychol* 56(4):601–620
- Menon V, Adelman NE, White CD, Glover GH, Reiss AL (2001) Error-related brain activation during a Go/NoGo response inhibition task. *Hum Brain Mapp* 12:131–143
- Mirabella G, Pani P, Pare M, Ferraina S (2006) Inhibitory control of reaching movements in humans. *Exp Brain Res* 174:240–255

- Morein-Zamir S (2003) Individual stopping times and cognitive control: converging evidence for the stop signal task from a continuous tracking paradigm. *Quart J Exp Psychol* 56a(3):469–489
- Morein-Zamir S, Nagelkerke P, Chua R, Franks I, Kingstone A (2004) Inhibiting prepared and ongoing responses: is there more than one kind of stopping? *Psychon Bull Rev* 11(6):1034–1040
- Oosterlaan J, Sergeant JA (1996) Inhibition in ADHD, aggressive and anxious children: a biologically based model of child psychopathology. *J Abnorm Child Psychol* 24:19–36
- Osman A, Sylvan K, Meyer DE (1986) The point of no return in choice reaction time: controlled and ballistic states of response preparation. *J Exp Psychol Hum Percept Perform* 12(3):243–258
- Osman A, Sylvan K, Meyer DE (1990) Does motor programming necessitate response execution? *J Exp Psychol: Human Percept Perform* 16(1):183–198
- Rieger M, Gauggel S, Burmeister K (2003) Inhibitor of ongoing responses following frontal, nonfrontal, and basal ganglia lesions. *Neuropsychology* 17:272–282
- Rubia K, Oosterlaan J, Sergeant JA, Brandeis D, Von Leeuwen T (1998) Inhibitory dysfunction in hyperactive boys. *Behav Brain Res* 94:25–32
- Rubia K, Smith AB, Brammer MJ, Taylor E (2003) Right inferior prefrontal cortex mediates response inhibition while mesial prefrontal cortex is responsible for error detection. *Neuroimage* 20:351–358
- Rubia K, Smith AB, Brammer MJ, Toone B, Taylor E (2005) Abnormal brain activation during inhibition and error detection in medication-naïve adolescents with ADHD. *Am J Psychiatr* 162:1067–1075
- Schachar R, Mota VL, Logan GD, Tannock R, Klim P (2000) Confirmation of an inhibitory control deficit in Attention-Deficit/Hyperactivity Disorder. *J Abnorm Child Psychol* 28:227–235
- Scheres A, Oosterlaan J, Swanson J, Morein-Zamir S, Meiran N, Schut H, Vlasveld L, Sergeant JA (2003) The effect of methylphenidate on three forms of response inhibition in boys with AD/HD. *J Abnorm Child Psychol* 31(1):105–120
- Scheres A, Oosterlaan J, Geurts H, Morein-Zamir S, Meiran N, Schut H, Vlasveld L, Sergeant JA (2004) Executive functions in boys with ADHD: primarily an inhibition deficit? *Arch Clin Neuropsychol* 19:569–594
- Sosnik R, Hauptmann B, Karni A, Flash T (2004) When practice leads to co-articulation: the evolution of geometrically defined movement primitives. *Exp Brain Res* 156(4):422–438
- Sosnik R, Hauptmann B, Karni A, Flash T (2006) The acquisition and implementation of the smoothness maximization motion strategy is dependent on spatial accuracy. *Exp Brain Res* 176(2):311–331
- Stark E, Drori R, Abeles M (2006) Partial cross-correlation analysis resolves ambiguity in the encoding of multiple movement features. *J Neurophysiol* 95:1966–1975
- Stewart JA, Tannock R (1999) Inhibitory control differences following mild head injury. *Brain Cognit* 41:411–416
- Tannock R, Schachar RJ, Carr RP, Chajczyk D, Logan GD (1989) Effects of methylphenidate on inhibitory control in hyperactive children. *J Abnorm Child Psychol* 17(5):473–491
- Torres E, Andersen R (2006) Space-time separation during obstacle-avoidance learning in monkeys. *J Neurophysiol* 96:2613–2632
- Torres E, Zipser D (2002) Reaching to grasp with a multi-jointed arm. I. Computational model. *J Neurophysiol* 88:2355–2367
- Van Boxtel GJM, Band GPH (2000) Inhibitory motor control in stop paradigms: reply to McGarry and Franks. *Acta Psychol* 105(1):79–82
- Van Boxtel GJM, Van der Molen MW, Jennings JR, Brunia CHM (2001) A psychophysiological analysis of inhibitory motor control in the stop-signal paradigm. *Biol Psychol* 58:229–262
- Van der Schoot M, Lichat R, Horsley TK, Sergeant JA (2005) Effects of stop signal modality, stop signal intensity and tracking method on inhibitory performance as determined by use of the stop signal paradigm. *Scan J Psychol* 46:331–341
- Viviani P, Flash T (1995) Minimum-jerk, two-thirds power law, and isochrony: converging approaches to movement planning. *J Exp Psychol Hum Percept Perform* 21(1):32–53
- Walton M, Gandhi NJ (2006) Behavioral evaluation of movement cancellation. *J Neurophysiol* 96:2011–2024
- Williams BR, Ponesse JS, Schachar RJ, Logan GD, Tannock R (1999) Development of inhibitory control across the life span. *Dev Psychol* 35(1):205–218