Stopping is not an option: the evolution of unstoppable motion elements (primitives)

Ronen Sosnik,1 Eliyahu Chaim,1 and Tamar Flash2
1Faculty of Electrical, Electronics and Communication Engineering, Holon Institute of Technology, Holon, Israel; and
2Department of Applied Math and Computer Science, Weizmann Institute of Science, Rehovot, Israel

Submitted 3 April 2015; accepted in final form 1 June 2015

Sosnik R, Chaim E, Flash T. Stopping is not an option: the evolution of unstoppable motion elements (primitives). J Neurophysiol 114: 846–856, 2015. First published June 3, 2015; doi:10.1152/jn.00341.2015.—Stopping performance is known to depend on low-level motion features, such as movement velocity. It is not known, however, whether it is also subject to high-level motion constraints. Here, we report results of 15 subjects instructed to connect four target points depicted on a digitizing tablet and stop “as rapidly as possible” upon hearing a “stop” cue (tone). Four subjects connected target points with straight paths, whereas 11 subjects generated movements corresponding to coarticulation between adjacent movement components. For the noncoarticulating and coarticulating subjects, stopping performance was not correlated or only weakly correlated with motion velocity, respectively. The generation of a straight, point-to-point movement or a smooth, curved trajectory was not disturbed by the occurrence of a stop cue. Overall, the results indicate that stopping performance is subject to high-level motion constraints, such as the completion of a geometrical plan, and that globally planned movements, once started, must run to completion, providing evidence for the definition of a motion primitive as an unstoppable motion element.

The ability to suppress an action that is no longer needed or to bring abruptly to an end an ongoing action is a hallmark of executive control. The stop-signal paradigm (Lappin and Eriksson 1966; Logan 1994; Verbruggen and Logan 2008) is widely used as a means of measuring inhibition of a potent action in a laboratory setting. In this task, subjects perform a visual-choice reaction-time task (responding to a “go” signal as quickly as possible) and are occasionally instructed to withhold their response when a “stop” stimulus follows the go stimulus (stop trials). It was found that 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 suppress a response and vice versa.

The increased difficulty to inhibit the response in the stop task when the SSD is increased (Logan 1994; Logan and Cowan 1984) 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” (De Jong et al. 1990; Logan 2015; Osman et al. 1986, 1990). There is currently a debate, however, when and where in the information-processing system it resides. 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 (van Boxtel et al. 2001), others have argued that it is a phantom, i.e., that there is no point in time that 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) (McGarry and Franks 1997; Osman et al. 1990). Moreover, with the assumption that the point of no return is not a phantom, it is not known yet whether it is merely a manifestation of low-level, peripheral constraints, such as the inability to impede muscles’ activations swiftly, or whether it is also subject to a high-level, central constraint (Verbruggen and Logan 2008).

Answering these questions may be facilitated by conducting experiments that enable the monitoring of overt motor performance, i.e., testing the kinematics or kinetics of the movement before and after a stop signal is presented. Several works have measured the termination of an action after it was already underway (Bachorowski and Newman 1990; Morein-Zamir 2003; Morein-Zamir et al. 2004). Overall, the findings suggested that the suppression of a preplanned movement and stopping an ongoing movement share the same stopping mechanisms (Morein-Zamir et al. 2004) and that stopping performance is dictated by two consecutive states: a cognitive state, in which the stop cue is processed, and a low-level state, in which the stopping performance is tied solely to the dynamic aspects of the movement (Boucher et al. 2007; Logan 2015; Logan and Cowan 1984; Morein-Zamir 2003).

Recently, it was shown that human subjects, who freely scribbled on a digitizing tablet looking for invisible targets randomly positioned in the workspace, have generated stereotypical, repetitive geometrical shapes, presumably with the aim of finding a motion strategy that maximizes reward (number of targets hit) (Sosnik et al. 2007b). The instruction of subjects to impede movement unexpectedly upon the hearing of an auditory cue (a stop cue) resulted in a velocity profile that was not a decelerating function of the time but rather, exhibited a complex pattern comprising one or more velocity peaks, thus implying an unstoppable motion element. Moreover, geometrical analysis showed 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 the pattern following the stop cue was positively correlated with the...
relative advance in the pattern rather than the amount of time that had elapsed from the movement initiation. Altogether, these findings suggested that the point-of-no-return phenomenon in humans is subject, at least to some extent, to high-level constraints, such as a completion of a kinematic geometrical plan, and could serve as an operative definition of motion primitives.

In this work, we aimed to continue studying the dependence of stopping performance on high-level motion features and test whether the ability (or inability) to bring abruptly to an end an ongoing movement is dependent on its evolving internal representation. To that end, we used the experimental paradigm presented in (Sosnik et al. 2004, 2007a), wherein we showed that asking subjects to connect four target points “as rapidly and as accurately as possible” resulted in a shift in the motion planning strategy throughout training—from the generation of a series of straight, point-to-point trajectories to the generation of curved trajectories, the latter maximizing motion smoothness. As many factors have been shown to affect reaction times, in general, and auditory reaction time, specifically, including fatigue (Namita and Shenvi 2010) and distraction (van den Berg and Neely 2006), we currently assessed the stop-cue processing time by recording EEG and detecting the N200 event-related potential (ERP), a negative-going wave found primarily over anterior scalp sites that peaks 180–320 ms poststimulus and was suggested to reflect inhibition of motor responses in go/no-go tasks (Brydges et al. 2012; Kaiser et al. 2006; Manuel et al. 2010) or conflict monitoring (Donkers and van Boxtel 2004; Heil et al. 2012; Zamorano et al. 2014).

**MATERIALS AND METHODS**

**Behavioral paradigm.** To learn to what extent stopping performance in adults is subject to modification due to changes in the internal representation of the task, a handwriting-like task was used. Fifteen healthy, right-handed subjects (nine men and six women, aged 20–54 yr) gave informed consent and participated in the study, which was approved by the Wolfson Medical Center Helsinki Committee. The only criterion used to determine which hand is dominant was the hand they reported using for writing. The experiment was composed of 20 blocks, each block lasting for 1 min. There was a 1-min rest between two consecutive blocks. Subjects were seated in front of a digitizing tablet (DrawingBoard VI, model 1218; GTCO CalComp, Scottsdale, AZ; active area 304.8 × 457.2 mm, resolution 1,000 lines/in., maximum data rate 125 packets/s, accuracy ±0.25 mm), and the height of the chair was adjusted individually at a convenient distance for the subjects to reach the table with a pen (Cordless Click Tip Pen; GTCO CalComp). To minimize friction, targets (black square frames of 20 × 20 mm) were printed on commercial transparencies that were attached to the surface of the digitizing tablet. Digital data were streamed to a computer disk for offline analysis. To remove the high-frequency, small jerky movements caused by physiological tremor, we smoothed the data with a sixth-order Butterworth filter, cut-off frequency 8 Hz.

The subjects were instructed to connect four target points (ABCD; returning to target A to complete an encirclement) with their dominant hand upon hearing an auditory cue (tone). Subjects were separated into two groups that practiced different target configurations, denoted I and II (Fig. 1A). Each subject practiced only one target configuration. Seven subjects trained on target configuration I, which had two pairs of highly, spatially co-aligned segments (obtuse angle; AB and BC; CD and DA), and eight subjects trained on target configuration II, which had only one pair of highly, spatially co-aligned segments (BC and CD).

**A** Target configuration I

<table>
<thead>
<tr>
<th>Vertical position (cm)</th>
<th>Horizontal position (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>18</td>
<td>22</td>
</tr>
<tr>
<td>C</td>
<td>A</td>
</tr>
<tr>
<td>B</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
</tr>
</tbody>
</table>

**B** Target configuration II

<table>
<thead>
<tr>
<th>Vertical position (cm)</th>
<th>Horizontal position (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>23</td>
<td>28</td>
</tr>
<tr>
<td>A</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>B</td>
</tr>
<tr>
<td>D</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 1.** Target configuration and N200 detection. A, left and right: target configurations I and II, respectively. The arrows denote movement direction. B: thin curves, EEG data of a representative training block comprised of 9 trials (subject #2, block 11); thick curve, block mean EEG data. Depicted are the manually detected N200 and P300 components.
Subjects were informed that occasionally (every 5 ± 1.5 s, mean ± SD), a beep (frequency 500 Hz, duration 100 ms) will be heard instructing them to impede their movement as rapidly as possible (stop cue) and that after a full stop is detected (tangential velocity falls below 2 cm/s and does not exceed 4 cm/s for the next 200 ms), a vocal message (“continue”) will be heard instructing them to recommence movement from the position where they left off. To motivate subjects to stop as rapidly as possible upon hearing a stop cue, they were told that they would be rewarded according to their stopping performance (“stopping reward”; i.e., the shorter the stopping time, the higher the reward). To motivate the subjects to connect the four target points as rapidly as possible (i.e., not generate slow movements to reduce stopping times), they were told that they would also be rewarded according to the number of traces (passing through all of the targets) that they complete in a block (“targets encirclement reward”). To prevent bias toward one motion strategy or the other (moving slowly or rapidly to maximize stopping reward or targets encirclement reward, respectively), no information was provided regarding the manner according to which movement performance or stopping performance was rewarded. Regardless of movement and stopping performance, the subjects were compensated for their participation in the experiment.

EEG recording and preprocessing. To identify the time that a stop cue is processed, we aimed at detecting N200. We recorded EEG signals (EEG100C; Biopac Systems, Santa Barbara, CA) from an electrode positioned over Fz. The recorded EEG was referenced to the right ear lobe, amplified (gain: 20,000; bandwidth: 0.1–35 Hz), and sampled (analog-to-digital resolution: 16 bits; sampling rate: 2,000 samples/s). The ground electrode was positioned over the right mastoid. Impedance for all electrodes was below 5 kΩ. As EEG is routinely contaminated with electro-oculogram (EOG), which may confound the detection of N200, we also recorded subjects’ eye movements and blinks with electrodes attached inferiorly to the orbital fossa of the right eye (for vertical eye movements) and to the external canthi (for horizontal eye movements).

The EEG data were decomposed into independent components (ICs) using the IC analysis method implemented in the EEGLAB toolbox (Delorme and Makeig 2004), based on the Runica algorithm. ICs related to EOG were detected and rejected using the ADJUST toolbox (Mognon et al. 2011).

Splitting the data set into discrete trials. For each block, the time points at which the tangential velocity first exceeded 4 cm/s following the occurrences of a continue vocal message were detected (motion recommence), and the data set was split into discrete trials—each trial consisting of data recorded between two consecutive motion recommences.

N200 detection. EEG reflects thousands of simultaneously ongoing brain processes; thus the brain response to a single stimulus or event of interest is not usually visible in the EEG recording of a single trial. To that end, the N200, as any other ERP, is detected when the response to a stimulus is averaged, causing random brain activity to be averaged out. In this study, the routine for N200 detection was conducted once for each block (comprising 9 ± 1 trials, mean ± SD) and involved the computation of a block mean EEG signal and a visual inspection of it looking for the N200/P300 complex—a negative-going wave that peaks 180–320 ms post-stimulus (Enriquez-Geppert et al. 2010) (Fig. 1B). For 14% of the blocks, an N200 could not be detected, due to a small number of trials (as a result of trial rejection).

The assumption that N200 genuinely marks the time of stop-cue processing (Brydges et al. 2012; Kaiser et al. 2006; Manuel et al. 2010) reflects a block’s mean stop-cue processing time, and as a result, the processing times of individual trials may be shorter or longer. This may occasionally result in an apparently odd finding, wherein a full stop is reached before a stop cue is actually processed (see Criteria for trial rejection, number 2, below). Albeit, the above-mentioned shortcoming, with the use of block N200, it is possible to detect loss of attention or evolving fatigue and changing the N200 accordingly, although at a single-block resolution rather than a single-trial resolution. The alternative option—setting an arbitrary processing time (e.g., 220 ms) for all blocks—may result in substantial underestimating or overestimating of processing time.

Criteria for trial rejection. For each trial, the entire data (psychophysical and physiological) were visually inspected. A trial was excluded from the analysis if one of the following was fulfilled: 1) the subject did not pass through all of the targets (found for 21 ± 18.9% of all trials, mean ± SD); 2) the time interval between the occurrence of a stop cue and motion full stop was below the detected N200—the time needed for the stop cue to be perceived (found for 2.4 ± 2.9% of all trials, mean ± SD); 3) the time interval between the occurrence of a stop cue and motion full stop was >1,500 ms, indicating nonadherence to task instructions (due to fatigue or momentary inattentiveness; found for 0.9 ± 1.6% of all trials, mean ± SD); 4) there were uncorrected EOG artefacts (eye blinks, eye movements) in the time interval between the occurrence of a stop cue and stop cue +350 ms, which may impair N200 signal detection (found for 0.8 ± 0.8% of all trials, mean ± SD).

Computing the projection of hand position. We aimed at testing whether the percent path traveled by the hand up to the time of full stop (“percent path covered up to full stop” index) is dependent on the percent path traveled by the hand up to the time of stop-cue processing, i.e., stop cue + N200 (“percent path covered up to stop cue + N200” index). As the exact length of the full path that would have been generated, had no stop cue occurred, was not known, the use of it for assessment of percent path to be covered was not feasible. Hence, the hand position at the time of stop cue + N200 or full stop was projected on the straight line connecting the target last visited and the succeeding target, and the Euclidean distance between the projected position and the last-visited target was computed.

To attain a normalized measure of the amount of shape covered (percent path covered), the following procedure was carried out.

For subjects who generated straight, point-to-point movements, we assumed the motion primitive to be a straight line. Thus the Euclidean distance between the projected position and the target last visited was divided by the Euclidean distance between the succeeding target and the target last visited; e.g., for a subject who was in the process of connecting targets D and A with a straight line—reached position $p^*$ (projected position $p^*$) at time stop cue + N200 and target $s^*$ (projected position $s^*$) at full stop (Fig. 2A)—the distances $p^*D$ and $s^*D$ were divided by the distance $AD$ to attain the percent path covered up to stop cue + N200 index and the percent path covered up to full stop index, respectively.

For subjects who coarticulated between adjacent segment pairs, we assumed a basic motion element to be a curved path. Thus the projected distance was divided by the sum of two intertarget distances; e.g., for subjects who were in the process of coarticulating between segment $AB$ and $BC$—reached position $p^*$ (projected position $p^*$) at time stop cue + N200 and position $s^*$ (projected position $s^*$) at full stop (Fig. 2B)—the distances $p^*A$ and $s^*B + BA$ were divided by the sum of distances $CB + BA$ to attain the percent path covered up to stop cue + N200 index and the percent path covered up to full stop index, respectively.

Comparing disturbed and undisturbed velocity profiles. We aimed at comparing the shape of the velocity profiles generated before and after time cue (e.g., $v^*$ for all segments—may inclusive to 12 undisrupted, point-to-point movements before an occurrence of a stop cue). To check invariance of a velocity profile shape, movements must be normalized for time and distance; thus we first detected the beginning and end of each movement (tangential velocity exceeds or falls below 2 cm/s, respectively) and split it into 100 equally spaced time points (using spline cubic interpolation), resulting in a time-normalized velocity profile. Next, the velocity amplitude of each movement was divided by the movement peak amplitude, resulting in amplitude and...
The fit to the "global planning" model is assessed using the following two indices:

\[
\text{Normalized \_velocity \_error} = \frac{\text{Vel}_{\text{model}} - \text{Vel}_{\text{data}}}{\text{Vel}_{\text{model}} + \text{Vel}_{\text{data}}}
\]

\[
\text{Normalized \_path \_error} = \frac{\text{Path}_{\text{model}} - \text{Path}_{\text{data}}}{\sqrt{\text{Path}_{\text{model}} - \text{Path}_{\text{data}}^2 + \text{Path}_{\text{curve} \_\text{length}}}}
\]

The path error was normalized by the sum of the path error and the length of the closed curve bounding the path error. To attain an index that is positively correlated with motion smoothness, the two normalized error indices were subtracted from 1.

As the two fit indices coevolved throughout training (i.e., an increase in the normalized velocity error of a movement was accompanied by an increase in the normalized path error and vice versa), a smoothness fit index was computed:

\[
\text{Smoothness \_fit \_index} = \frac{\text{Normalized \_velocity \_error} + \text{Normalized \_path \_error}}{2}
\]

Finally, with the assumption that neighboring segments were co-planned for the coarticulating subjects and as coarticulation between motion segments was found to evolve only for highly, spatially coaligned segments (as was also found in Sosnik et al. 2004, 2007a), the global planning model was applied for segment ABC (connecting segments AB and BC) and for segment CDA (connecting segments CD and DA) for target configuration I and for segment BCD (connecting segments BC and CD) for target configuration II. The procedure was repeated for all movements generated before the occurrence of a stop cue (i.e., undisturbed movements).

Detecting the position of the point of no return. To study the dependence of stopping performance and existence of a point of no return on the evolution of coarticulation motion strategy and motion primitive throughout training, the actual data were compared with the predictions of the minimum jerk model (Flash and Hogan 1985; Sosnik et al. 2004). The minimum jerk model assumes that given a start position, end-point position, and the position of one or more via-points (the path locations at which a local minimum velocity is attained, corresponding to the point of local maximum curvature), the system preplans an entire hand trajectory that passes through all of these points with the smoothest possible (minimum jerk) trajectory. The objective cost function (cost) to be minimized is the square of the magnitude of the jerk (rate of change of acceleration) of the hand velocity.

Smoothness fit index

\[
\text{Smoothness \_fit \_index} = \frac{\text{Normalized \_velocity \_error} + \text{Normalized \_path \_error}}{2}
\]

The path error was normalized by the sum of the path error and the length of the closed curve bounding the path error. To attain an index that is positively correlated with motion smoothness, the two normalized error indices were subtracted from 1.

As the two fit indices coevolved throughout training (i.e., an increase in the normalized velocity error of a movement was accompanied by an increase in the normalized path error and vice versa), a smoothness fit index was computed:

\[
\text{Smoothness \_fit \_index} = \frac{\text{Normalized \_velocity \_error} + \text{Normalized \_path \_error}}{2}
\]

Finally, with the assumption that neighboring segments were co-planned for the coarticulating subjects and as coarticulation between motion segments was found to evolve only for highly, spatially coaligned segments (as was also found in Sosnik et al. 2004, 2007a), the global planning model was applied for segment ABC (connecting segments AB and BC) and for segment CDA (connecting segments CD and DA) for target configuration I and for segment BCD (connecting segments BC and CD) for target configuration II. The procedure was repeated for all movements generated before the occurrence of a stop cue (i.e., undisturbed movements).

Detecting the position of the point of no return. To study the dependence of stopping performance and existence of a point of no return on the evolution of coarticulation motion strategy and motion primitive throughout training, the actual data were compared with the predictions of the minimum jerk model (Flash and Hogan 1985; Sosnik et al. 2004). The minimum jerk model assumes that given a start position, end-point position, and the position of one or more via-points (the path locations at which a local minimum velocity is attained, corresponding to the point of local maximum curvature), the system preplans an entire hand trajectory that passes through all of these points with the smoothest possible (minimum jerk) trajectory. The objective cost function (cost) to be minimized is the square of the magnitude of the jerk (rate of change of acceleration) of the hand velocity.

Smoothness fit index

\[
\text{Smoothness \_fit \_index} = \frac{\text{Normalized \_velocity \_error} + \text{Normalized \_path \_error}}{2}
\]
processing a stop cue resulted in a stopping position 75% or more of the distance between targets B and C (i.e., stopping close to target C).

2) To test whether the left bound represents a point of no return, i.e., the processing of a stop cue after passing the left bound would always result in a stopping position close to the final target, or whether it represents the beginning of an intermediate zone in which the stopping position is sometimes close to the final target, we detected the “right bound”—the farthest point from the left bound, at which processing of a stop cue resulted in stopping 25% or less of the distance between the second and the third target; e.g., for trials in which segments BC and CD were partially coarticulated, the right bound was set as the closest point to the left bound, at which processing a stop cue resulted in a stopping position 25% or less of the distance between targets C and D (i.e., stopping close to target C).

RESULTS

The N200 across subjects was 219 ± 26 ms (mean ± SD), with one subject (#14) having a mean N200 significantly lower (195 ms) than the other subjects ($P = 0.0009$, $F = 2.72$, $df = 14$, one-way ANOVA, performing multiple comparisons of the group means). To test whether there is a significant change in N200 throughout practice, indicating tiredness or loss of attention that can prohibit rapid response to the stop cue, we compared the N200 values found for the first 10 blocks with the N200 values found for the last 10 blocks. No significant change in N200 was found throughout practice for any of the 15 subjects ($P > 0.05$, Student’s two-tailed t-test).

Four subjects (denoted as “noncoarticulating”)—two subjects practicing target configuration I and two subjects practicing target configuration II—generated straight, point-to-point trajectories with roughly bell-shaped velocity profiles throughout the entire training period. The remaining subjects (denoted as “coarticulating”)—five subjects practicing target configuration I and six subjects practicing target configuration II—have changed motion planning strategy throughout training, from generating four straight, point-to-point trajectories in the first training blocks to generating one (in target configuration I) or two (in target configuration II) curved trajectories by the end of the last training block. As expected, the transition from generating straight, point-to-point trajectories to generating curved, coarticulated trajectories was accompanied with a significant increase (+24.7%) in trial mean velocity (comparing data from the first five blocks with data from the last five blocks, excluding data recorded from stop cue + N200 to full stop). For the noncoarticulating subjects, the trial mean velocity increased throughout training, although more moderately (+14.2%; Table 1).

All subjects—stopping time is very weakly correlated with motion velocity. We aimed at studying whether the processing of a stop cue (stop cue + N200) would be followed by a decelerated velocity profile, implying prompt initiation of a stopping process. To that end, we counted the number of velocity peaks (velocity amplitude that is higher than 20 cm/s and exceeds 0.15 of the trial peak velocity), following the time of stop-cue processing. For the noncoarticulating and coarticulating subjects, the trial percent for which one, two, or three additional velocity peaks were found was 32, 6, and 0.3% ($n = 573$) and 40, 9, and 2% ($n = 1,477$), respectively, indicating that the stopping process did not commence at the time that a stop cue was processed (Fig. 3).

To validate that stopping performance is not dependent/not solely dependent on low-level kinematic features of the movement, we examined the correlation between the instantaneous velocity at stop cue + N200 and the time that has elapsed from stop cue + N200 to full stop (see MATERIALS AND METHODS for “full stop” definition). Had the ballistic motion been tied solely with low-level kinematic features, such as velocity, then the total movement duration, in general, and the duration of the decelerated phase, specifically, would have correlated positively with peak velocity (Ghez et al. 1995). Thus a stop cue that is processed while the hand velocity is higher will result in a longer stopping time and vice versa. Surprisingly, a correlation between the two descriptors ($P \leq 0.05$) was found for only two subjects (out of 15; Table 1). For both subjects, the correlation was very weak and positive. Overall, this finding suggests that the stopping process did not commence at the time that a stop cue was processed and that it is not dependent/not solely dependent on low-level kinematic features of the movement.

Next, we aimed at testing whether stopping performance is dependent on high-level motion features, such as the existence of an unstoppable geometrical shape. The subsequent analyses were performed separately on the noncoarticulating and coarticulating subjects.

Noncoarticulating subjects—a straight, point-to-point movement is an unstoppable motion element. We first computed the percent trials in which each of the four subjects stopped on target (percent path covered up to stop cue + N200 = 90–110%), although disturbed by a stop cue. With averaging over the subjects, the group mean percent trials were high (73 ± 9.9%, mean ± SD), indicating that the subjects generally completed the motion, regardless of the position on the path at which the hand resided at the time a stop cue was processed or that most of the stop cues were processed while the hand

| Table 1. A very weak correlation between trial mean velocity and stopping time |
|------------------------------|------------|-----------------------------|
| Subject # | Velocity change, % | Correlation between velocity and stopping time, coefficient of determination |
| Coarticulating |
| Target configuration I | 2 | 24.4 (n = 42.30) | $R^2 = 0.06$ (n = 137) |
| 3 | -16.8 (n = 173.2) | N.C. (n = 82) |
| 4 | 26.4 (n = 38.19) | N.C. (n = 139) |
| 6 | 14.9 (n = 30.19) | $R^2 = 0.05$ (n = 94) |
| 7 | 34.9 (n = 24.41) | N.C. (n = 140) |
| Target configuration II | 8 | -17.5 (n = 12.38) | N.C. (n = 96) |
| 9 | N.C. (n = 12.22) | N.C. (n = 80) |
| 10 | 59.8 (n = 42.29) | N.C. (n = 146) |
| 11 | 9.7 (n = 42.36) | N.C. (n = 137) |
| 12 | 32.9 (n = 30.20) | N.C. (n = 80) |
| 15 | N.C. (n = 13.23) | N.C. (n = 83) |
| Noncoarticulating |
| Target configuration I | 1 | 10.8 (n = 31.29) | N.C. (n = 114) |
| 5 | 5.1 (n = 26.35) | N.C. (n = 131) |
| Target configuration II | 13 | 16.2 (n = 41.38) | N.C. (n = 164) |
| 14 | 24.6 (n = 31.20) | N.C. (n = 69) |
approached the second target. A qualitative inspection of the results revealed that the processing of a stop cue at a position midway between targets (i.e., percent path covered up to stop cue + N200 = 50) resulted in a final hand position close to the second target (i.e., percent path covered up to full stop, ~100; Fig. 4A). Surprisingly, the final hand position was close to the second target also when a stop cue was processed at a position closer to the first target (Fig. 4B). Furthermore, the processing of a stop cue while the hand was at a position closer to the second target was occasionally followed by a stopping position close to the third target (percent path covered up to full stop, close to 200); i.e., the subjects have not only reached the second target but have also connected the second target with the third target with a straight path (Fig. 4C). A quantitative analysis across subjects has confirmed that the mean hand position at full stop was close to the second target (93 ± 12%, mean ± SD) if the hand has covered <60% or >80% of the intertargets’ distance at the time of stop cue + N200 (Fig. 4D), suggesting that a straight, point-to-point movement can act as an unstoppable motion element. The covering of 60–80% of the intertargets’ distance by the time of stop cue + N200 resulted sometimes (25% of the trials) in reaching the third target (190–250%), with a mean hand position of 137 ± 33% (mean ± SD) at full stop.

To test whether the temporal features of the disturbed movements resembled the undisturbed counterparts, we grouped the four noncoarticulating subjects’ movements and split them into an undisturbed group (n = 1,652), containing straight, point-to-point movements that were completed before the processing of a stop cue, and a disturbed group (n = 165), containing straight, point-to-point movements that were completed after the processing of a stop cue. No significant difference between the velocity profiles of the two groups was found for any time point, indicating that completed disturbed and undisturbed movements had a similar temporal profile.

Coarticulating subjects—a globally planned movement is an unstoppable motion element. To study whether an inability to impede an action of coarticulation swiftly between two adjacent segments is tied to the planning and internal representation of the two segments as a unitary motion element, we first computed motion smoothness for undisturbed trials. It was found that for most of the coarticulating subjects (eight out of 11), motion planning strategy was not stable throughout training; subjects occasionally reverted to the generation of straight, point-to-point trajectories, possibly with the aim of finding the motion strategy that maximizes reward. As the motion planning strategy was found to be stable within a single trial (SD of a trial fit indices ≤0.1), we assumed a trajectory being disturbed by a stop cue would have had (had it not been disturbed) a smoothness fit index equal to the mean of the fit indices of the undisturbed trajectories in that trial.

Next, the smoothness fit indices of the 11 coarticulating subjects were pooled and split into three groups.

1) Noncoarticulating group; comprised of trials, each having a mean fit index of 0.35–0.55, which corresponds to the connection of adjacent targets with a straight, point-to-point trajectory. These trials were found in early training blocks for all of the coarticulating subjects and sporadically throughout training for eight coarticulating subjects.

2) “Partially coarticulating” group; comprised of trials, each having a mean fit index of 0.55–0.75, which corresponds to a partial coarticulation between adjacent segments. These trials were found for all of the coarticulating subjects and reflect an intermediate stage in motion-performance evolution (shifting from generating straight, point-to-point trajectories to the generation of maximally smooth, curvilinear path). These trials were found for all of the coarticulating subjects and reflect
the final stage in motion-performance evolution—the global planning of the two segments as a unitary, smooth motion element.

For the first group (noncoarticulating trials), the generation of straight paths was not disturbed by an occurrence of a stop cue (Fig. 5); e.g., for segment ABC, a stop cue that was processed at a point residing between targets A and B or between targets B and C resulted in the connection of the two targets (i.e., AB or BC) with a straight path and stopping at target B or C, respectively (for improved visibility, only the last encirclement of the targets before the time of stop-cue processing is presented). The arrows depict movement direction. D: the abscissa was split into 10 equally spaced intervals, and the means ± SD of the movement data for each interval were computed and plotted. Surprisingly, the mean hand position at full stop was closer to the 2nd target also when the hand at the time of stop-cue processing was closer to the 1st target. The passing of 60–80% of the intertargets’ distance by the time of stop-cue processing resulted occasionally in reaching the 3rd target (percent path covered up to full stop, ~200%).

For the second group (partially coarticulating trials), stopping performance exhibited characteristics common to both the first and third groups (noncoarticulating and highly coarticulating trials), respectively.

For the third group (highly coarticulating trials), the generation of a curved trajectory was not disturbed by an occurrence of a stop cue (Fig. 5); e.g., for segment CDA, a stop cue that was processed at a point residing between targets C and D resulted in the coarticulation between the two segments (i.e., CD or DA) and stopping at target A (Fig. 5). The center of the intermediate zone resided close to the first target (15, 4, and 6% for segments ABC, CDA, and BCD, respectively), and the width of the intermediate zone was narrow (2% for all segments), suggesting that the globally planned segments were internally represented as unitary motion elements that had to run to completion.

For the second group (partially coarticulating trials), stopping performance exhibited characteristics common to both the first and third groups (noncoarticulating and highly coarticulating trials), respectively.
noncoarticulating and highly coarticulating trials, implying an intermediate stage in motion internal representation (shifting motion planning strategy from the generation of two straight paths to the generation of a globally planned, curved path). The generation of a partially curvilinear path was only occasionally disturbed by the occurrence of a stop cue; e.g., for segment BCD, a stop cue that was processed at a point residing 40% or less of the distance between targets B and C resulted in a stopping position at target C, whereas a stop cue that was processed at a point residing 20% or more of the distance between targets C and D resulted in a stopping position at target D (Fig. 5). A stop cue that was processed while the hand resided anywhere between these two points resulted in a final hand position between the second and third target. Moreover, whereas the right bound for the partially coarticulating trials was close to the right bound found for the noncoarticulating trials, the left bound for the partially coarticulating trials was close to the left bound found for the highly coarticulating trials, resulting in an overall wide intermediate zone (33, 33, and 37% for segments ABC, CDA, and BCD, respectively).

**DISCUSSION**

In this work, we aimed at testing whether the ability to bring abruptly to an end an ongoing movement is dependent on high-level kinematic attributes, such as the internal representation of the movement as a smooth, coarticulated movement, or is dependent solely on low-level kinematic constraints, such as the velocity at the time that a stop cue was processed. To that end, we motivated subjects to make rapid, ballistic movements by rewarding them according to the amount of targets’ encirclement done and tested whether the ballistic movements—simple (straight lines) or complex (curved paths)—could be swiftly impeded, regardless of the velocity or hand position at the time that a stop cue was processed. We used scalp-recorded N200, which enables a per-subject, neural-based segregation of the internal processing of a stop cue, yielding finer and more accurate analyses of stopping characteristics. We found that a stop cue was followed frequently by additional velocity peaks (Fig. 3) and that the amount of time taken to reach a full stop was not correlated or very weakly correlated with velocity (Table 1), suggesting that stopping
performance does not depend solely on low-level motion constraints.

To test whether the ability to impede an ongoing action swiftly is tied with high-level motion attributes, such as the completion of a geometrical shape, we tested whether stopping performance is dependent on the percent of path covered by the hand at the time a stop cue is processed. A stop cue processed after motion initiation, whether in the course of connecting two consecutive targets with a straight line (Figs. 4 and 5) or coarticulating between two adjacent segments, forming a curvilinear path (Fig. 5), resulted in the completion of the geometrical shape, regardless of the percent path covered by the hand at the time that a stop cue was processed, indicating that both of the geometrical shapes can be regarded as unstoppable motion elements. The inability to impede an ongoing action swiftly was tied with its internal representation as a smooth, unitary action; a stop cue that was processed while partially coarticulating between two adjacent segments (moderate fit index) did not result in motion completion, and the stopping position was dependent on the percent path covered by the hand at the time of stop-cue processing (Fig. 5).

The following sections discuss the current findings focusing on the nature of unstoppable motion elements and stopping mechanism.

Stopping mechanism. Previous works studying the mechanisms involved in withholding movement suggested the existence of two independent, competing processes: a go process, which is triggered by the presentation of a go stimulus and comprises two stages—a controlled stage and a ballistic stage—and a stop process, which is triggered by the presentation of a stop signal (Logan and Cowan 1984). If the stop process finishes before the controlled go process, then response inhibition is successful, and no response is emitted; hence, the probability of withholding a response depends on the relative finishing time of the go process and stop process and not on their relative starting times. Our findings suggest that the independence between the “start and stop” processes is also valid for ongoing movements, provided that it is perceived as a unitary action plan; the processing of a stop cue while motion is on the run will result in action completion, regardless of the percent path covered by the hand up to the time that the stop cue is processed. The manifestation of the point-of-no-return phenomenon can be readily observed by comparing the overt, spatiotemporal features of the movements following the processing of a stop cue with the spatiotemporal features of undisturbed movements.

Motion completion was found to depend on a spatial boundary; the covering of a certain percent of the path resulted in motion termination, regardless of the time needed to cover that portion (Fig. 4D), suggesting that stopping performance may be tied to task constraints—geometrical in our paradigm.

A motion primitive—an unstoppable motion element. The notion of dynamic, unstoppable motion elements was introduced by Mussa-Ivaldi and Bizzi (2000), who showed that the premotor circuits within the spinal cord of spinalized frogs and rats are organized into a set of discrete modules. Each module, when activated, induces an unstoppable, specific force field, and the simultaneous activation of multiple modules leads to the vectorial combination of the corresponding fields. The unstoppable motion elements in our study exhibited kinematic features; inability to impede an ongoing movement was linked with its internal representation as a single, globally planned movement, as defined by the fit of the generated trajectory to the maximal smooth trajectory.

The notion of an unstoppable kinematic motion element was suggested by Henis and Flash (1995), who formulated the “superposition” model for target-switching experiments. It was suggested that arm-trajectory modification in a double target-displacement paradigm might involve the vectorial summation of two independent plans, each coding for a smooth, point-to-point, straight trajectory. The first plan is the initial, unmodified plan for moving between the initial hand position and the first target location. The second plan is a time-shifted trajectory plan that starts and ends at rest and has the same amplitude and kinematic form as a simple, point-to-point movement between the first and second target locations. The current finding—that a straight path, when generated in the context of a geometrical task, can act as an unstoppable motion element—supports the plausibility of the use of two straight, point-to-point movements in a target-switching task, a generated trajectory being a superposition of two unstoppable, point-to-point, straight movements.

Apparently, our finding of a dependence of stopping performance on high-level motion features, rather than on low-level motion attributes, opposes previous studies involving a kinematic task (Bachorowski and Newman 1990; Morein-Zamir 2003). However, the characteristics of stopping performance may be tied with task constraints, regardless of the nature of the task (be it kinematic or dynamic); in the cursor-following task (Morein-Zamir 2003), in which subjects were instructed to track a moving target continuously on a computer screen with the mouse cursor and impede movement as rapidly as possible upon the occurrence of a stop cue, both the velocity profile and shape of the path were dictated by the position and velocity of the moving target. Thus stopping performance (i.e., 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 1990), in which subjects were instructed to trace a circle continuously and impede the movement as rapidly as possible upon the occurrence of a stop cue, no constraint was imposed on the temporal profile of the movement, but the shape of the path was predefined. As the experimental paradigm used in this study did not impose temporal or spatial constraints (apart from having to pass through all of the targets), it presumably motivated a shift in the internal representation of the task and the evolution of motion primitives whose attributes are dictated by the geometrical features of the trajectory.

Automaticity and control are commonly perceived as opposites; automatic processes do not suffer interference from current tasks (Posner and Snyder 1975; Shiffrin and Schneider 1977). Our findings support this notion; when a movement was regarded as a unitary action, it was automatically generated (ballistic) and thus could not be controlled and was run to completion. However, it may be that automaticity reflects a shift in the way a task is controlled, rather than abdication of control. This notion was suggested by Logan (1982), who found no evidence that keystrokes were ballistic in skilled typists; subjects were able to inhibit writing an entire word after perceiving a stop cue, although the writing of an entire word is believed to be automatic in skilled typists (hence, the basic unit is smaller than a word). It may be, however, that the
brain keeps two representations for a word being written: typed or pronounced; apart from a holistic, high-level, internal representation, a lower representation, comprising each of the building blocks (letters) constituting the word, still exists, allowing control processes to take over automaticity when needed. It may be that for drawing and scribbling movements, the internal representation of the basic building blocks, be they straight lines or curved paths, is lost when the elements are perfectly blended (coarticulated) to form a globally planned, unitary, complex shape, hence, resulting in loss of control over the basic elements. This notion is supported in this study, showing that partially curvilinear, coarticulated segments that were yet to be globally planned and internally represented as a unitary, complex motion could be stopped before completion.

Open questions. The findings of the current study raise several questions.

1) To test whether preplanned, ballistic movements can act as unstoppable motion elements, we rewarded the subjects for the number of targets’ encirclement, thus motivating them to generate rapid movements. The findings indicated a weak correlation between motion velocity and stopping performance (Table 1). It is conceivable to assume that a stop cue processed while in the course of connecting two targets with a straight path or coarticulating between two adjacent segments would result in a premature termination of the action had the subjects generated a slow movement (i.e., not ballistic). Alternatively, scaling up the scene by a factor of five would probably not result in a fivefold increase in peak velocity (exceeding 5 m/s), and thus the movement will take longer to be completed, and it may no longer be ballistic and/or be internally represented as a basic motion element, allowing its premature termination. Thus it is of interest to test whether the weak correlation between velocity and stopping performance and the behavioral phenomena described in the study are valid only for trials for which the peak velocity is above a certain threshold, and/or the total movement duration is below a specific threshold.

2) Assuming the size of the “motor buffer” holding the motor plan is finite, it would be of interest to study what is the maximal complex trajectory that is still unstoppable, and does the complexity relate to the geometrical features of the task, or does it depend on task characteristics?

3) We previously showed in a functional MRI study (Sosnik et al. 2014) that there is a strong correlation between the amount of activation in the contralateral primary motor cortex (M1-L) and trial mean velocity, supporting earlier findings that the M1-L region encodes low-level motion kinematic features (Ifelt et al. 2011; Moran and Schwartz 1999). The amount of activation in the contralateral premotor dorsal was found to correlate with trajectory shape, implying its role in coding higher-level attributes of the motion. Following our current findings on the dependence of stopping performance on high-level motion features, it would be of interest to study whether different stopping processes (low and high level) engage distinct neural substrates and whether these neural substrates mediate both motion initiation and termination.

4) The “encirclement reward” (i.e., amount of money rewarded per one encirclement) of the targets was known a priori to the subjects, whereas no specific information was given regarding the dependency of the stopping reward on stopping performance (stopping time). The subjects were only informed that they will be rewarded according to their stopping time—

the shorter the stopping time, the higher the reward. It would be interesting to study whether the evolution of coarticulated, motion primitives and stopping performance is dependent on a cost function-maximizing reward in the face of uncertainty regarding the time of stop-cue occurrence and the dependency of stopping reward on stopping performance.

Overall, it was proposed previously that task characteristics have a major role in setting motor performance, such as shaping the attributes of the acquired motion planning strategy and primitives throughout training (Sosnik et al. 2004, 2007a). Our current findings suggest that the characteristics of the task and accordingly, the motor plan, being geometrical in our study, also dictate the attributes of the stopping mechanisms and performance and hint at the tremendous versatility, sophistication, and adaptability of the motor system.

ACKNOWLEDGMENTS

The authors thank Irit Sella for her helpful comments and suggestions regarding the analysis, interpretation, and readability of the manuscript.

GRANTS

Support for this research was provided by the Israel Science Foundation (Grant No. 76/12).

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

Author contributions: R.S. conception and design of research; E.C. performed experiments; R.S. analyzed data; R.S. and T.F. interpreted results of experiments; R.S. prepared figures; R.S. drafted manuscript; R.S. and T.F. edited and revised manuscript; R.S. and T.F. approved final version of manuscript.

REFERENCES


The point of no return: a fundamental limit on the ability to control an act of control.


