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CONTROLLED MOVEMENT PROCESSING: EVIDENCE FOR A COMMON INHIBITORY CONTROL OF FINGER, WRIST, AND ARM MOVEMENTS

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Abstract—We used the behavioral task and theoretical construct of the countermanding paradigm to test whether there is any difference between the inhibitory control of the finger, wrist, and arm. Participants were instructed (primary task) to respond to a directional go signal presented at the fovea by pressing a button with either their index or middle fingers, moving a joystick with their wrists, or reaching to a stimulus on a touch screen with their arms. They were also instructed (secondary task) to withhold their responses when a stop signal was presented on 25% of trials. The participants' ability to inhibit each of the commanded movements was captured by their inhibition probability function, which describes how withholding is increasingly difficult as the delay between the go and stop signals increased. By modeling each participant's inhibition function, we estimated that the time needed to inhibit a commanded movement was about 240 ms, a variable that did not differ significantly between the three limb segments. Moreover, we found that the best-fit model of each segment's inhibition function could fit equally well the inhibition functions obtained with the other two segments. These results provide evidence that the upper limb segments share a common inhibitory control, which may facilitate the regulation of neuronal activity within the distributed motor cortical representations and thus simplify the voluntary control of multi-segmental movements.

Key words: inhibition, finger, wrist, arm, countermanding, stop.

INTRODUCTION

The voluntary control of goal-directed forelimb movements entails the precise coordination of their individual segments (Jeannerod, 1984, 1995). For example, during reaching there is a proximal to distal sequence of activation of motor cortex neurons, and hence of limb muscles, from shoulder and elbow to wrist and finger muscles (Murphy et al., 1985). Such multi-joint movements are generally functionally coupled through mechanical linkages and muscle synergies, which themselves are reflected in distributed and overlapping motor cortical representations (see for review Schieber, 2001; Flanders, 2005). Primary motor cortex is indeed characterized by the absence of spatially discrete within-limb somatotopy (Rathelot and Strick, 2006). The major constraints to such an organization are the convergence of multiple cortico-spinal projections to single motoneuronal pools (Asanuma and Rosén, 1972; Kwan et al., 1978; Gould et al., 1986) and the divergence of single cortico-spinal projections to multiple motoneuronal pools (Fetz and Cheney, 1978; Buys et al., 1986; McKiernan et al., 1998). In addition, motor cortex neurons are densely interconnected through axon collaterals (Huntley and Jones, 1991; Tokuno and Tanji, 1993), which may further help mediate coordinated activation of cortico-spinal projections to motoneuronal pools activating muscles in different limb segments.

The voluntary control of movements encompasses not only the ability to execute coordinated movements but also the ability to inhibit an already commanded movement. The coordination of limb movements raises the question of whether the voluntary inhibition of limb segments is also concerted.

The inhibitory control of movements has been extensively studied with the countermanding paradigm, which provides both a behavioral task and a theoretical framework (Logan, 1994). Two countermanding studies have previously suggested that a single inhibitory control could be exerted on different motor acts, such as the tracking of visual objects by pursuit and saccadic eye movements (Kornylo et al., 2003) and the displacement of gaze with coordinated eye and head movements (Corneil and Elsley, 2005). Two other studies examining the inhibitory control of eye and arm movements suggested otherwise (Logan and Irwin, 2000; Boucher et al., 2007). More recent studies, which combined trans-cranial magnetic stimulation (TMS) and motor evoked potentials (MEP), have suggested that the countermanding of a particular movement can be accompanied, in some contexts, with a non-specific suppression of cortico-motor excitability (Coxon et al., 2006; Badry et al. 2009; Cai et al., 2012; Majid et al., 2012; Greenhouse et al., 2012).

Here we used the countermanding paradigm to investigate the inhibitory control of three upper limb segments

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Abbreviations: IFG, inferior frontal gyrus; MEP, motor evoked potentials; MPFC, medial aspects of prefrontal cortex; pre-SMA, pre-supplementary-motor area; RT, reaction time; SSD, stop signal delay; SSRT, stop signal reaction time; TMS, trans-cranial magnetic stimulation; VLPFC, ventro-lateral aspects of prefrontal cortex.

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that are functionally coupled when reaching to grasp an object, namely, the finger, the wrist, and the arm (Jeannerod, 1984), with the assertion that any difference in the inhibitory control of these segments would refute the hypothesis that there is a unique inhibitory control of the limb.

EXPERIMENTAL PROCEDURES

Participants

We tested nine right-handed human adults (age: 25–40 years) who had normal or corrected-to-normal vision and no known movement disorders. They performed three different countermanding tasks – each involving only finger, wrist, or arm movements – in three different blocks whose sequence was counterbalanced between participants. All experiments were undertaken with the understanding and written consent of each participant. The experimental procedures complied with The Code of Ethics of the World Medical Association (Declaration of Helsinki, 1964) and were approved by the local ethics board.

Tasks and apparatus

Participants were tested in a dimly lit room. They sat 45 cm in front of the computer monitor (17-inch Sony MultiScan 200GS, 1024 × 768, 60 Hz non-interlaced) positioned on a table, with their heads fixed by a chin rest and their right hands positioned in front of them on the table and aligned with their body midline. The monitor was equipped with a capacitive touch screen (ELO TouchSystems, Menlo Park, CA). Visual stimulus presentation and data acquisition were controlled by software using Matlab and the Psychophysics Toolbox (Brainard, 1997) running on a Pentium IV computer.

Each trial started with the appearance at the center of the monitor of two parallel vertical lines (2 × 11 pixels separated by 2 pixels). Following a variable delay (800–1200 ms), these central lines were replaced by a leftward- or rightward-oriented arrow (12 × 12 pixels), which acted as a go signal and whose orientation was randomized between trials. In the **primary task** (go trials), participants were asked to keep their gaze on the visual stimuli and make either a finger, wrist, or arm movement in the direction indicated by the arrow as quickly as possible. The **finger task** involved the pressing of one of two push buttons with the index or middle finger of the right hand. The buttons were firmly attached to the table, aligned with the participant's midline, and oriented perpendicular to the monitor. The electrical contact produced by the button press (through serial port data acquisition, 13-kHz sampling rate) signaled the onset of the finger movement. Since the subjects performed the task with their fingers lying on each button and given the extremely short difference between the button pressing starting and end time, we assumed the button pressing time as the time when the finger movement began. The **wrist task** involved moving a joystick from its central starting position with the right hand. The joystick (Gravis Analog Pro) was attached to the table in front of the participant, aligned with their body midline, and connected to a PC sound card (44.1-kHz sampling rate). The sound card transformed the movement of the joystick in a voltage value, where the middle starting position corresponded to 0 mV, the extreme leftward position of the bar corresponded to −10 mV and the extreme right horizontal position to +10 mV. We defined as onset of the wrist movement the horizontal position of the bar that generated a voltage value lower than −4 mV for the leftward movements and higher than +4 mV for the rightward movements (40% of the excursion in each direction). The **arm task** involved producing a reach for the right hand from a push button to a target area (contour line, 200 × 200 pixels) positioned 12° (293 pixels) on either side of the central go signal and always present during the entire block of trials. The push button was also attached to the table in front of the participant and aligned with their body midline. The release of the button press (through serial port data acquisition, 13-kHz sampling rate) defined the onset of the reach and the touch screen signal verified whether its landing position was correct.

In the **secondary task** (stop trials), which constituted 25% of the total trial number, a red square (200 × 200 pixels) was presented at the center of the display to instruct the participant to cancel the commanded motor response and remain still at the starting position. This **stop signal** appeared after a variable delay following the go signal – the stop signal delay (SSD, see Fig. 1A), which was set on the basis of the participant's current performance using a staircase algorithm. The SSD was increased by 50 ms after each successfully canceled stop trial and decreased by 50 ms after two consecutive non-canceled stop trials. In the finger task subjects had to withhold the button press, in the wrist task they had to keep the joystick bar in the middle starting position and in the arm task subjects were required to keep starting position button press.

For each countermanding task, participants performed 5 blocks of 80 trials, each block starting with a 50-ms SSD. Software computed online the participant's reaction time (RT), the time elapsed from the onset of the go signal to the initiation of the movement. When RT exceeded 1 s, the trial was aborted. Correct and incorrect go trials were signaled to subjects by two different acoustic stimuli. Another acoustic stimulus was presented when RT exceeded 500 ms to act as feedback for the participant to respect the primary task's demand of responding as quickly as possible.

Data analysis

We used the race model described by Logan and Cowan (1984) to model the behavioral performance of the participants during the three countermanding tasks and estimate the time to cancel a commanded movement in response to the stop signal, the stop signal reaction time (SSRT). The model assumes that the behavior in stop trials results from a race between two independent processes – a GO process initiated by the go signal and a STOP process initiated by the stop signal – racing to cross a finish line (Fig. 1A). When the GO process is fast and finishes first, the movement fails to be canceled (non-canceled trials). When the STOP process finishes first, the movement is successfully canceled. Because the model assumes these processes to be independent, the duration of the GO process is given by the distribution of RT in the go trials (Fig. 1B, C, *thin curve*). The STOP process duration cannot, however, be directly measured, but it is reflected in the inhibition function that describes the probability of non-canceled trials across the range of SSD (Fig. 1B, C, *thick curve*). We estimated SSRT by averaging the results of two methods derived from the race model, because these methods are equally valid (Logan and Cowan, 1984).

The **integration method** (Fig. 1B) provides an estimate of SSRT for each SSD assuming that the SSRT is constant. For each given SSD, the instant at which the STOP process ends is obtained by integrating the RT distribution in go trials until the integral matches the probability of non-canceled trials for that SSD. The SSRT then equals this instant minus the SSD. This method is very sensitive to small sample size as well as to irregularities in the tails of the inhibition function and RT distribution. We therefore averaged all the SSRT obtained from each SSD for which there were at least 10 stop trials and the probability of non-canceled trials was within 0.15–0.85, which captured the linear portions of the distributions.

The **mean subtraction method** (Fig. 1C) considers the SSRT as a random variable and estimates it as the difference between the mean RT in go trials and the mean of the inhibition function. To calculate the mean value of the inhibition

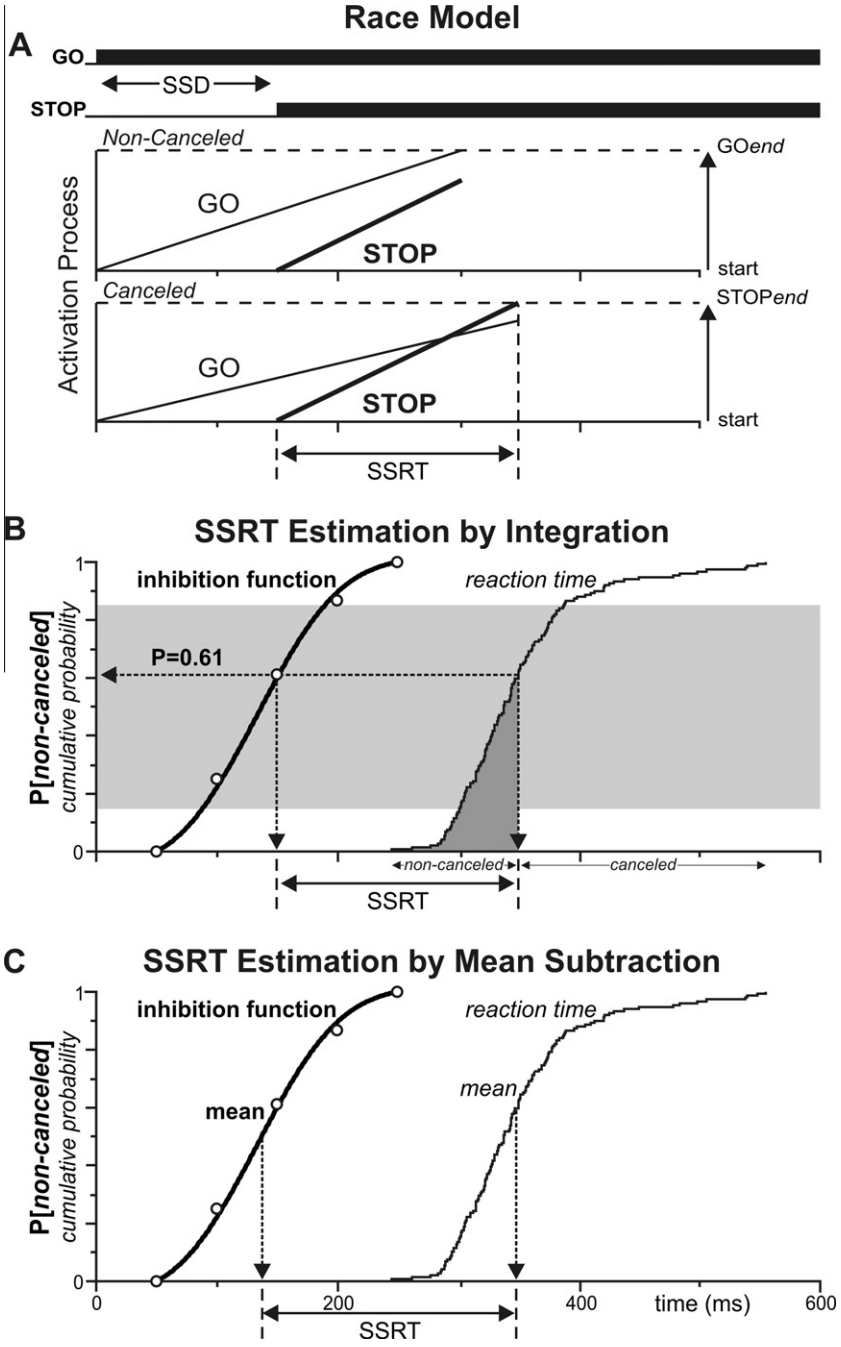

Fig. 1. (A) Schematic of the countermanding paradigm's behavioral task and race model. (B, C) Representative inhibition function (*thick curve:* probability of non-canceled stop trials as a function of SSD) and saccade RT distribution (*thin curve:* cumulative probability of go-trial RT) obtained in one participant. The integration method (B) estimates SSRT for a given SSD by integrating the go-trial RT distribution until the integral equals the probability of non-canceled stop trials obtained at that SSD (e.g., 0.61). The corresponding vertical arrow delimits the RT of movements that would not have been canceled if a stop signal had been presented (darkened portion). The shaded area highlights the 0.15–0.85 range of probabilities considered in the analysis. The mean subtraction method (C) estimates SSRT by subtracting the mean of the inhibition function from the mean go-trial RT. See text for further details.

function, we treated the latter as cumulative distribution and converted it into a probability density function. These data were then fit with a function of the form: $W(t) = \gamma - (\gamma - \delta) \times \exp[-(t/\alpha)^{\beta}]$, where t is the time after the go signal, α is the time at which the function reaches 64% of its full growth, β is the slope, γ and δ are, respectively, the maximum and minimum values of the function (Weibull, 1951). The mean of this function was calculated as the difference between the probability of non-canceled trials for a given SSD [$W(t)$] and the probability for the preceding delay SSD [$W(t-1)$] multiplied by the given SSD summed over all SSD (Logan and Cowan, 1984). To account for the fact that several inhibition functions had a minimum of >0 and a maximum <1, we rescaled the function by dividing its mean by the difference between the maximum and the minimum probabilities of non-canceled trials. The mean inhibition function was thus given by: $(\sum[W(t) - W(t-1)] \times t)/$

$[W(t_{max}) - W(t_{min})]$, where t ranges from the minimum to the maximum SSD in 1-ms intervals (Hanes et al., 1998; Paré and Hanes, 2003).

The inhibition functions obtained in the three countermanding tasks were compared after converting the data obtained from each participant into the standardized relative finishing time described by Logan and Cowan (1984): $ZRFT = (RT_{mean} - SSD - SSRT)/RT_{SD}$, where RT_{mean} and RT_{SD} are, respectively, the mean and standard deviation of the RT in go trials. The standardized inhibition function in each task, which relates the probability of non-canceled trials to ZRFT scores across participants, was fit with a Weibull function of the form described above.

RESULTS

The mean RT and SSRT values obtained from each participant for each limb segment and movement direction are shown in Fig. 2, and their averages are given in Table 1. Comparable RT was observed for finger and wrist movements, but the arm RT was somewhat longer, especially for leftward movements. The SSRT, estimated as the average value between the integration and the mean subtraction methods (see methods), showed less variability between limb segments and movement directions, and it averaged 236 ms.

A two-way MANOVA—with limb segment and movement direction as factors, RT and SSRT as dependent variables—revealed a significant effect on the dependent variables (Wilk's λ, $F = 3.34$, $p < 0.01$). A one-way MANOVA indicated a significant effect of limb segment on the dependent variables ($F = 4.69$, $p < 0.01$), but no significant effect of goal direction ($F = 0.73$, $p = 0.49$). There was no significant interaction. Multiple regression models further revealed that there was a significant correlation between RT and the two factors ($R^2 = 0.30$, $F = 7.22$, $p < 0.01$), which could be accounted for by the significant correlation between RT and limb segment ($t = 4.25$, $p < 0.01$); there was no correlation with movement direction ($t = -1.17$, $p = 0.25$). Post-hoc comparisons indicated that the arm RT was significantly longer than that of the finger ($t = 3.78$, $p < 0.001$) and the wrist ($t = 3.28$, $p < 0.005$). There was no significant correlation between SSRT and the two factors ($R^2 = 0.08$, $F = 1.35$, $p = 0.27$; limb segment: $t = -0.17$, $p = 0.87$; movement direction: $t = 1.58$, $p = 0.12$).

To validate our SSRT estimates, we needed to confirm that our data complied with the race model's basic requirement, namely, that the probability of non-canceled trials grew with increasing SSD (Logan and Cowan, 1984). The example shown in Fig. 1B, C illustrates such compliance. Across participants, the probability of non-canceled trials grew from an average of 0.05 (SD = 0.10, min = 0, max = 0.38) at the shortest SSD to an average of 0.93 (SD = 0.09, min = 0.7, max = 1.0) at the longest SSD. Further tests of the adequacy of the race model are related to how well it can predict the RT of those movements that failed to be canceled; for all the following comparisons, we only considered SSD with at least five non-canceled trials. The model's assumptions first predict that RT in non-canceled trials should lengthen with increasing SSD, because gradually more movements can escape inhibition as the stop signal is delayed. This was indeed a common observation as the mean RT of the non-canceled movements produced when the stop signal was presented at a given SSD was longer than that of the movements produced at the immediately shorter SSD in 85% (75/88) of the available comparisons; examples for each task are shown in Fig. 3A–C. The mean of the distribution of these RT differences was significantly different than 0.0 (t-test, $p < 0.001$) in each task (Fig. 3D–F). A second prediction of the model is that the mean RT in non-canceled trials should be shorter than that observed in go trials, i.e., in the absence of the stop signal, because the distribution of the former is but a truncated version of the latter (Fig. 1B). We found this to be the case in 85% (120/141) comparisons, as exemplified again in Fig. 3A–C. The mean of the distribution of these RT differences was significantly different than 0.0 (t-test, $p < 0.001$) in each task (Fig. 3G–I). Finally, to fully account for the participants' behavior, the model should be able to predict the actual RT of these non-canceled movements. The RT predicted by the model for the movements produced at each SSD is that of each go-trial movement initiated before the finish line of the STOP process relative to that SSD (Fig. 1B, shaded RT portion to the left of the vertical arrow). We found that the difference between the mean of the RT observed in non-canceled stop trials and the mean of that predicted by the model was significant (t-test, $p < 0.05$) in only 16% (22 out 141) of comparisons. The mean of the distribution of these RT differences was not significantly different than 0.0 (t-test, $p = 0.60$, 0.98, and 0.24) in each task (Fig. 3J–L). We conclude from these analyses that the race model described accurately the behavior of the participants performing these tasks.

The invariance of our SSRT estimate across tasks shown in Table 1 supports the hypothesis that the three limb segments are under the control of a common inhibitory mechanism. We tested further this hypothesis by examining whether the ranks of the SSRT estimates across subjects were maintained between tasks. If participants with long SSRT in one task also had long SSRT in each other task, the difference in ranking of their corresponding SSRT would be minimal. Fig. 4A shows the SSRT observed in each participant across the three tasks. The SSRT of each subject in each task was rank ordered and the sum of the absolute rank differences was calculated: $(|rank_{(arm)} - rank_{(wrist)}| + |rank_{(arm)} - rank_{(finger)}| + |rank_{(wrist)} - rank_{(finger)}|)$. The cumulative distribution of the sum of the observed differences in SSRT ranks (Fig. 4B, solid line) was relatively small and significantly smaller than the distribution of the sum of all possible ($n = 729$) differences (Fig. 4B, *dashed line*) (Fisher Exact test, $p < 0.01$).

We also examined the inhibitory control of the three limb segments by comparing all the inhibition functions obtained from our participants after combining leftward and rightward trials; this was possible because the differences between the corresponding SSRT estimates were not statistically significant (see above). The large number of trials thus provided a more accurate estimation of the ability to inhibit a movement. Fig. 5A shows each

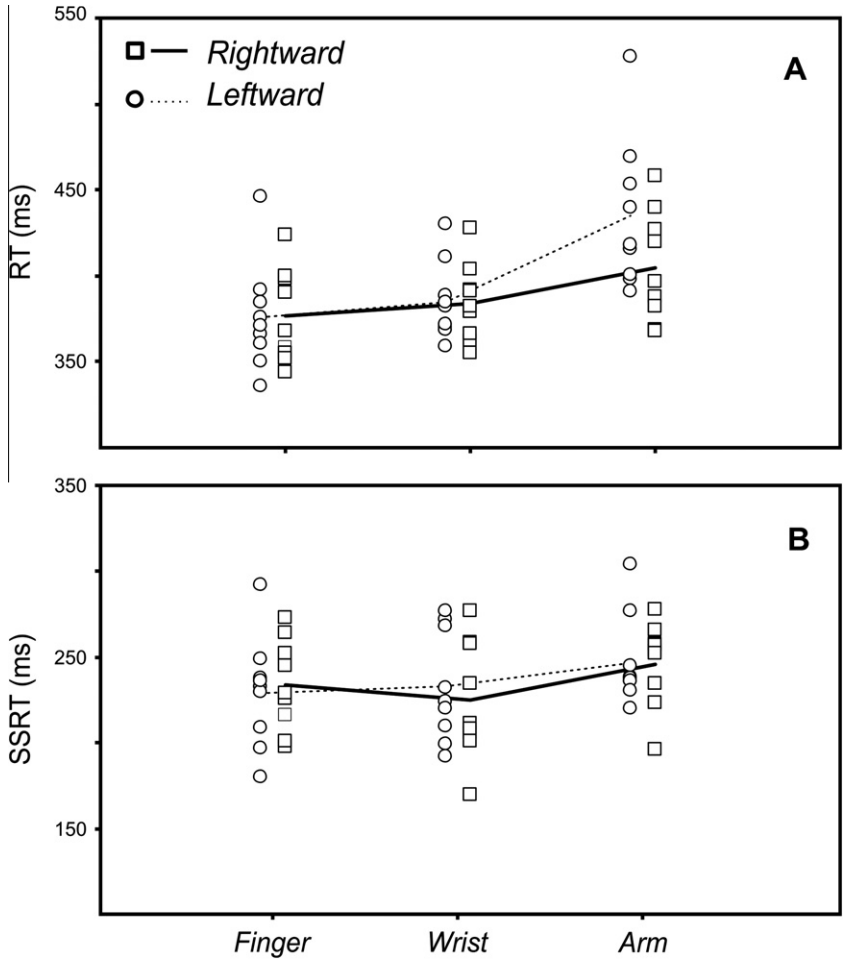

Fig. 2. Single-subject RT and SSRT for finger, wrist and arm movements. Across-subject mean RT (A) and SSRT (B) are shown for rightward (solid lines) and leftward (dotted lines) movements.

Table 1. RT and SSRT estimates (mean ± SE; in milliseconds) for each segment and movement direction

	Finger		Wrist		Arm	
	Leftward	Rightward	Leftward	Rightward	Leftward	Rightward
RT	376 ± 10	377 ± 9	385 ± 7	384 ± 7	435 ± 15	405 ± 11
SSRT *integration*	227 ± 12	230 ± 8	229 ± 9	218 ± 14	249 ± 11	244 ± 10
SSRT *mean subtraction*	232 ± 10	237 ± 19	236 ± 12	232 ± 11	246 ± 8	249 ± 7
SSRT *average*	229 ± 11	234 ± 9	233 ± 10	225 ± 11	247 ± 9	247 ± 8

participant's inhibition function for each limb segment in terms of the probability to cancel a movement as a function of SSD. We standardized these data by computing their ZRFT scores (see Experimental procedures). According to the race model, the probability to inhibit a movement depends not only on the SSD, but also on the RT of movements made in the go trials as well as the SSRT (Logan and Cowan, 1984). Fig. 5A–D indeed confirms that the inhibition functions become gradually more uniform as more variables are considered. This outcome is further evidence that the race model faithfully accounted for the participants' performance, which validates again the SSRT estimations that we obtained (Logan and Cowan, 1984). Fig. 5D shows the standardized inhibition functions associated with the three limb segments. We first modeled each segment's inhibition function with a best-fit Weibull curve and then used each Weibull model to account for the inhibition function of the other two segments. Near-perfect goodness-of-fit was obtained for each inhibition function's model (finger: $R^2 = 0.95$; wrist: $R^2 = 0.89$; arm: $R^2 = 0.93$). Most importantly, each of these models accounted equally well for the inhibition functions of the other two segments (finger model: wrist $R^2 = 0.89$, arm $R^2 = 0.93$; wrist model: finger $R^2 = 0.92$, arm $R^2 = 0.92$; arm model: finger $R^2 = 0.95$, wrist $R^2 = 0.88$). These results further support the hypothesis that the inhibitory control of the three limb segments is indistinguishable.

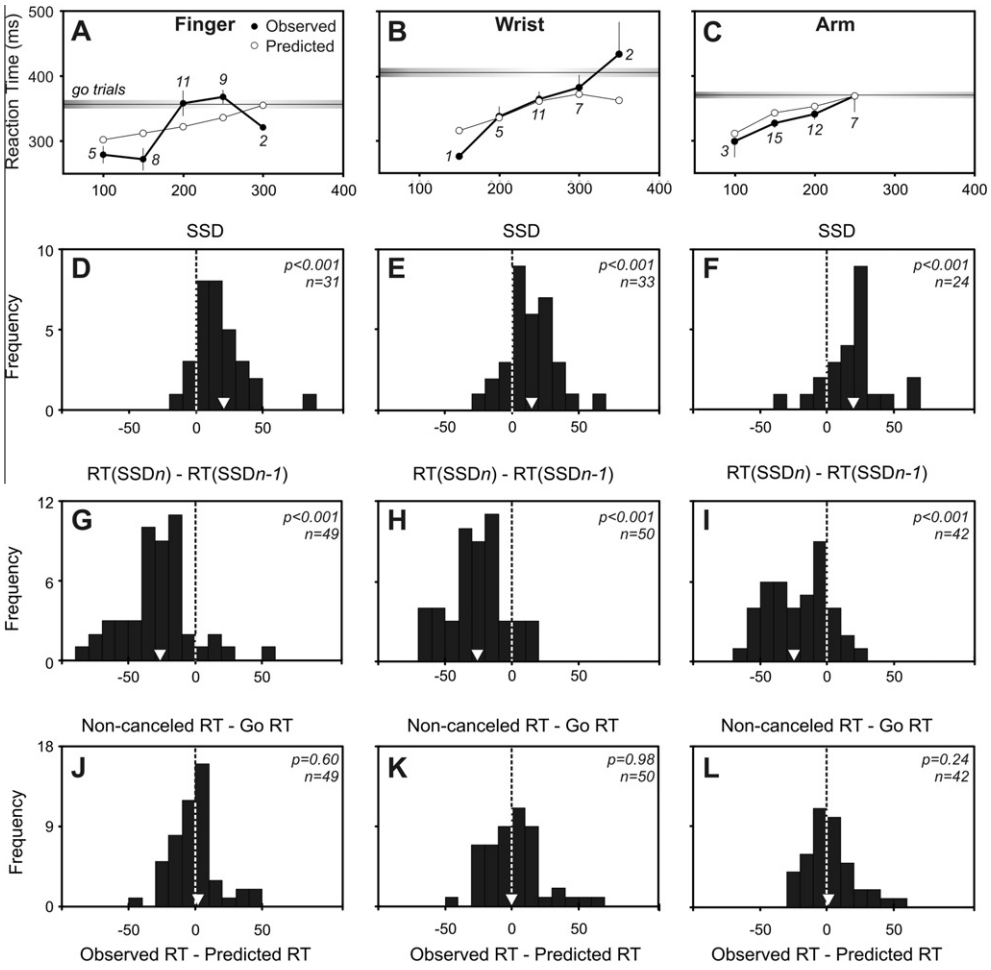

Fig. 3. Representative mean (±SE) RT of movements produced by one participant in non-canceled stop trials (●) along with that predicted by the race model (○) as well as in go trials (shaded stripe) for the finger (A), wrist (B) and arm (C) tasks. The number of non-canceled stop trials at each SSD is indicated; quantitative analyses considered only SSD with at least 5 non-canceled trials. (D–F) Distribution of the differences between the mean RT in non-canceled stop trials at a given SSD and that obtained at the shorter SSD for movements made in both directions. (G–I) Distribution of the differences between the mean RT in non-canceled stop trials at each SSD and that observed in all go trials. (J–L) Distribution of the differences between the mean RT in non-canceled trials and that predicted by the race model. *Arrowhead:* mean of distribution; *p*: probability that the distribution is not statistically different from zero.

DISCUSSION

We used the behavioral task and the theoretical constructs of the countermanding paradigm to test whether there is any difference in the inhibitory control of the finger, wrist, and arm. With the premise that a simple race model between GO and STOP processes faithfully accounted for countermanding performance of the subjects across tasks, we found that the estimated time needed to cancel a commanded movement (SSRT) between the three upper limb segments did not differ significantly and that the ranks of estimated times across subjects were maintained between tasks. In addition, the best-fit model of each segment's inhibition function could fit equally well the inhibition functions obtained with the other two segments. Although we tested each segment independently, our results suggest the presence of a common inhibitory control. Nevertheless, the alternative hypothesis—the inhibition of each limb segment is controlled separately but with identical time course—remains plausible.

Our SSRT estimates are within the range found in previous studies of healthy human participants countermanding single limb movements, including finger (e.g., Logan and Cowan, 1984; Logan and Irwin, 2000; Cavina-Pratesi et al., 2001; Van der Shoot et al., 2003; Morein-Zamir et al., 2004; Coxon et al., 2006, 2007), hand (e.g., Boucher et al., 2007), and arm movements (e.g., Mirabella et al., 2006). Our study adds to this literature by suggesting that the neuronal activity that regulates the movements of these limb segments is modulated in the same way when these are countermanded. Together with other countermanding studies (Kornylo et al., 2003; Corneil and Elsley, 2005; Goonetilleke et al., 2010), our results support the hypothesis that a single inhibitory control is exerted on different motor acts when these are functionally coupled, i.e., when their neural regulation is shared. It is therefore reasonable to predict that a single inhibitory control also regulates the production of the coordinated movements of the lower limb segments as in locomotion (Lacquaniti et al., 2002) and perhaps other coordinated movements involving

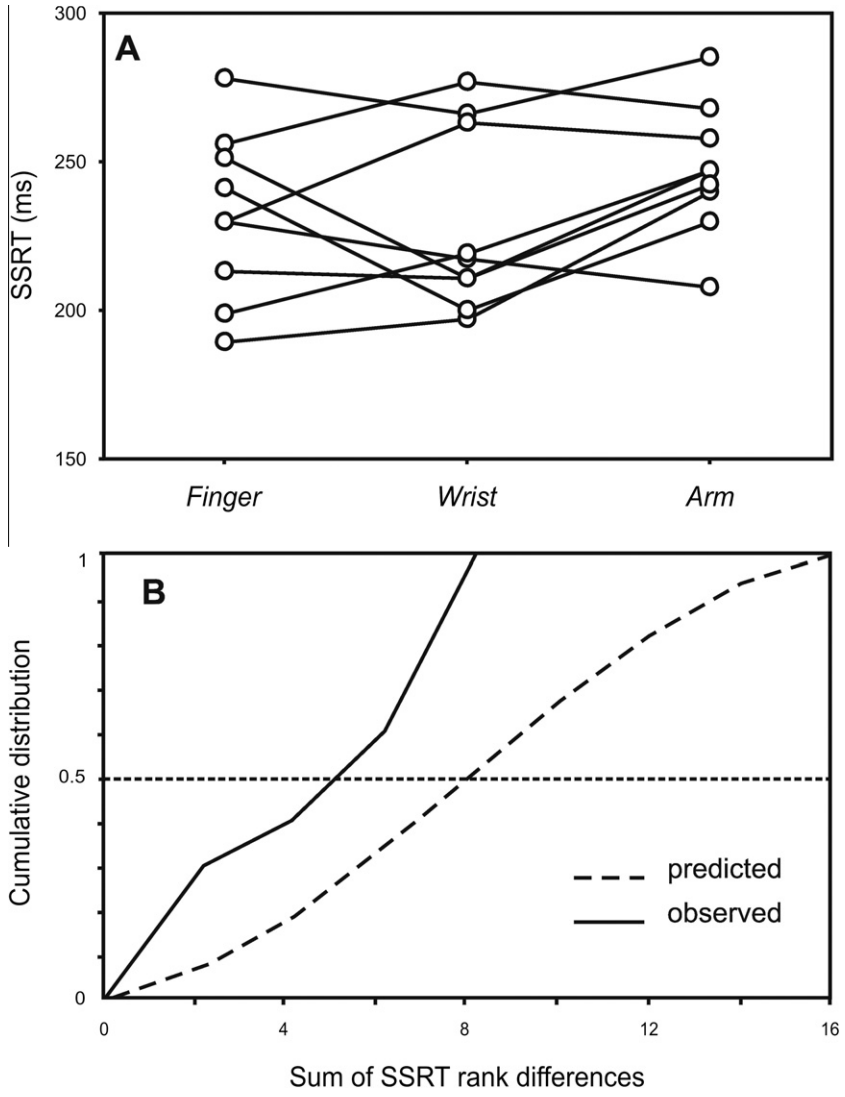

Fig. 4. Rank analysis of SSRT obtained in the different tasks. (A) SSRT estimate for each subject in each task. (B) Cumulative distribution of the sum of the absolute differences in SSRT ranks for the nine subjects (solid line; observed) and for all permutations (dashed line; predicted). The result from a Fisher Exact test indicates that the probability for the observed sum of SSRT ranks to be less than 9 (versus greater than 9) was significantly higher than what was predicted by chance.

seemingly unrelated effectors, e.g., hand–mouth coordination in feeding (Lee et al., 1999) and speech (McNeill, 1992). How this inhibitory control is exerted is a problem that is actively investigated.

The inhibitory control manifested in the countermanding task has been attributed to a neural circuit that includes the medial (MPFC) and ventro-lateral (VLPFC) aspects of prefrontal cortex as well as the basal ganglia direct and hyper-direct pathways (see for review Verbruggen and Logan, 2008; Chambers et al., 2010; see also Jahfari et al., 2011). Three recent fMRI (Functional Magnetic Resonance Imaging) studies speak of whether a common inhibitory control is involved in countermanding the responses of different effectors. Spatial overlap in BOLD signals from both the pre-supplementary-motor area (pre-SMA within MPFC) and the right inferior frontal gyrus (IFG within VLPFC) was found between countermanded eye and hand responses (Leung and Cai, 2007), hand and speech responses (Xue et al., 2008), and hand and foot responses (Tabu et al., 2012). These results are only suggestive of a common inhibitory control, because fMRI does not resolve whether the exact same neuronal populations are involved. A non-selective inhibitory control is also suggested by recent TMS/MEP studies showing some suppression of cortico-motor excitability on task-irrelevant muscles when finger (Coxon et al., 2006), hand (Badry et al., 2009; Majid et al., 2012; Greenhouse et al., 2012), and speech responses (Cai et al., 2012) are successfully countermanded. In these studies, MEP suppression of task-irrelevant muscles was limited to approximately 10–20% and was not widespread; it is not clear whether the tested muscles are generally recruited in coordinated movements. This suppression also depended on the timing of the stimulation relative to the stop signal presentation, being absent when delivered either

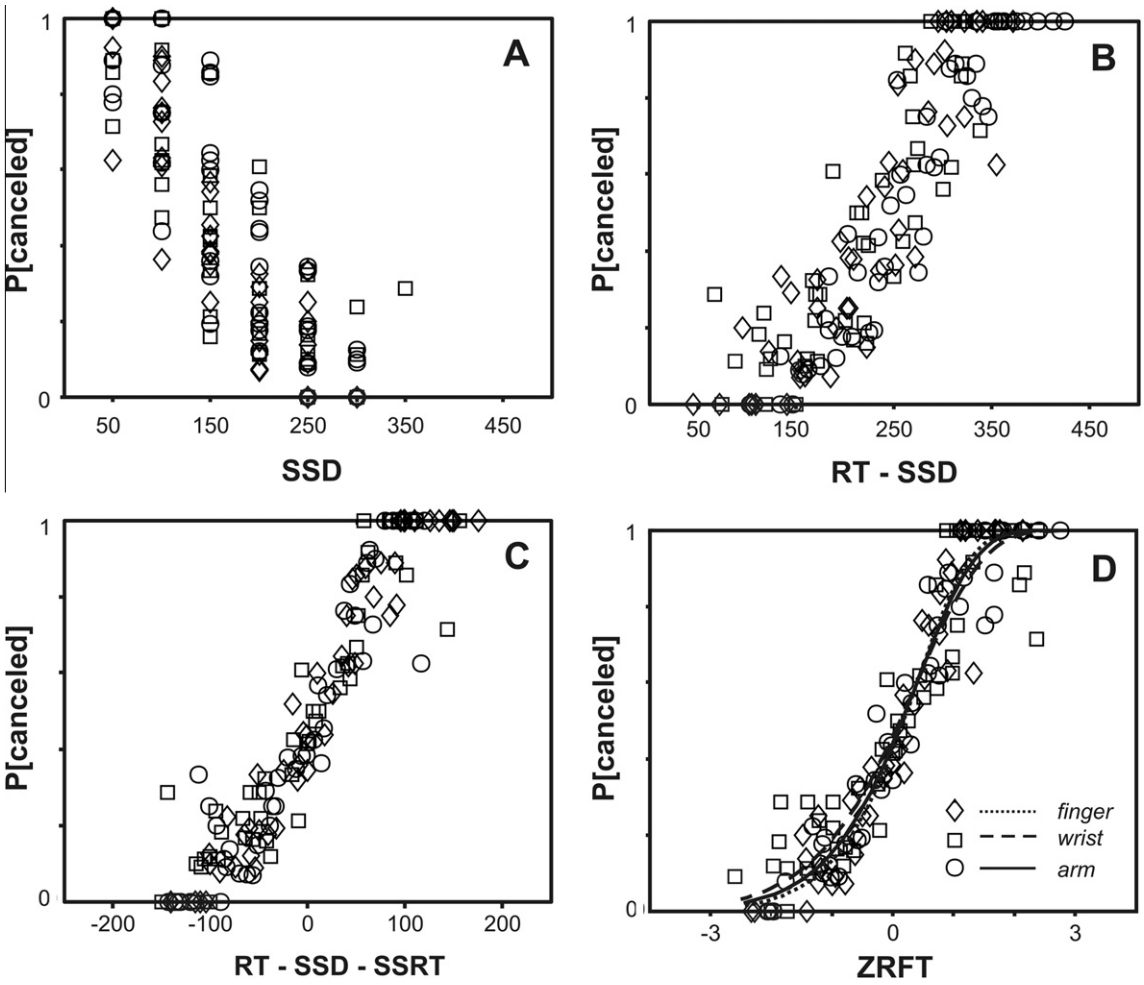

Fig. 5. (A) Standardization of inhibition functions. Probability of successfully canceled stop trials as a function of SSD (A), RT minus SSD (B), and RT minus SSD and SSRT (C) for all participants and limb segments. (D) Probability of successfully canceled stop trials as a function of ZRFT scores and best-fit Weibull curve for each limb segment.

before it or late after, i.e., periods during which selective inhibitory control could be exerted (see also Coxon et al., 2007).

How could pre-SMA or right IFG inhibit motor outputs? One prevailing hypothesis is via the activation of a subcortical route, which involves the basal ganglia indirect and hyper-direct pathways, and leads to an increase in thalamo-cortical inhibition (Band and van Boxtel, 1999; Aron and Poldrack, 2006; Aron, 2007; Jahfari et al., 2011). Alternatively, the local network of inhibitory horizontal connections within the primate primary motor cortex (Jacobs and Donoghue, 1991) could be recruited via cortico-cortical projections (Miyachi et al., 2005). A significant increase in intra-cortical inhibition, as suggested by TMS/MEP studies (e.g., Coxon et al., 2006) could then quell cortical motor commands and thus countermand the movement of a limb segment. The selectivity of such mechanism is, however, constrained by the imprecise somatotopy in both the primary motor cortex (Rathelot and Strick, 2006) and the subthalamic nucleus (Romanelli et al., 2004; Miyachi et al., 2006). It may therefore be that only a coarsely selective inhibition can be effected. Relatively separate intra-cortical inhibitory circuits could be sharing a common source of inhibitory control signals.

An alternative hypothesis is that inhibitory control is a distributed process and that different circuits are required for inhibiting movements made by different effectors. Evidence for this alternative hypothesis includes the difference in the length of time needed to cancel a manual response versus an eye movement (Logan and Irwin, 2000; Boucher et al., 2007) or a verbal response (Xue et al., 2008); some correlation across subjects was, however, found in the later report. The fMRI study of Curtis et al. (2005) suggested that the inhibitory control of eye movements was contained within the oculomotor system, relegating the withholding of other motor modalities to different neural circuitry (Curtis, 2008). Potential candidates for providing inhibitory signals to suppress saccade-related activity within the primate frontal eye field (Hanes et al., 1998) and superior colliculus (Paré and Hanes, 2003) are fixation neurons, which rapidly raised their activity in advance of a countermanded saccade and presumably inhibit movement neurons by activating interneurons. Neurons with identical properties have not been identified within the skeletomotor system. The only available candidates are neurons recorded in the primate dorsal premotor cortex that have been observed to transiently increase their activity before countermanded

reaches (Mirabella et al., 2011). These neurons, perhaps activated by PFC inputs or by pre-SMA neurons (Johnson and Ferraina, 1996), could provide feedforward inputs to inhibitory inter-neurons in primary motor cortex (Ghosh and Porter, 1988; Tokuno and Nambu, 2000), whose activation would lead to the increase in local inhibition indirectly observed when movements are countermanded (Coxon et al., 2006). Putative inhibitory inter-neurons have been identified in primary motor cortex, but their activity has not been sufficiently studied (Merchant et al., 2008; Vigneswaran et al., 2011; see also Swadlow, 1994; Beloozerova et al., 2003). Evidence thus far only suggests a role in shaping the spatial tuning of pyramidal neuron activity, as it has been reported in prefrontal cortex (Wilson et al., 1994; Rao et al., 1999; Constantinidis and Goldman-Rakic, 2002). As it stands, we lack important information to substantiate a common inhibitory mechanism across motor systems.

Similarities between the eye movement and skeletomotor systems have also been observed in the discharges of frontal eye field (Hanes et al., 1998) and superior colliculus (Paré and Hanes, 2003) movement neurons with some neurons in the dorsal premotor area during limb movements (Mirabella et al., 2011). The activity of these neurons increases before movement initiation and it is rapidly suppressed within the SSRT when the movement is countermanded. These findings, especially if extended to primary motor cortex, could potentially represent the neural substrates underlying the countermanding of the limb segment movements examined in this study.

CONCLUSION

With the use of the countermanding paradigm, we found that the inhibition of finger, wrist, and arm movements does not differ in its temporal aspect. This can be taken as evidence for a non-selective, inhibitory control. Such a control could promote quick and complete cancellation of goal-oriented limb movements when they are deemed inappropriate and thereby facilitating their correction.

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