

# The presence of visual gap affects the duration of stopping process

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**Abstract** A milestone on which relies the voluntary control of behavior is the ability to shape our motor output to meet the needs of the context which we are continuously facing. Even though it is solidly established that contextual information influence movement generation few studies have so far explored their effects on inhibitory processes. We compared the inhibitory control of arm movements of ten healthy right-handed volunteers in a countermanding reaching paradigm with and without the presence of a temporal gap between the offset of the central target and the peripheral target appearance. We found that this perceptual gap reduces the reaction times of hand movements and, at the same time, increases the duration of the stop process, the stop signal reaction time. The two effects are not correlated implying that inhibition and execution of reaching movement are two independent processes influenced by a common factor: the disengagement of selective attention from the central target. Therefore our results support the idea of the existence of a link between spatial selective attention and inhibitory processes.

**Keywords** Reaching · Countermanding task · Visual gap · Inhibition · Arm

## Introduction

Being able to stop a planned movement is a core ability of voluntary control, since it allows to shape the motor behavior accordingly to the context in which a subject acts.

The countermanding task (Logan 1994; Logan and Cowan 1984) is one of the most frequently used tasks in the study of behavioral inhibition. In this paradigm, a subject's ability to control the production of voluntary movements is probed by randomly intermixing two tasks in a single experimental block. Participants usually perform a speeded choice reaction time task (no-stop trials). Occasionally and at variable intervals [stop signal delays (SSD)] from the go signal, a stop signal is presented to inform the participants to withhold their response (stop trials). On short SSDs, participants can easily suppress their response. By contrast, when the SSD is long enough, participants will nearly always execute the response. Logan and Cowan (1984) developed the horse-race model to explain these results. The model assumes that the behavioral outcome of the task is the result of a race between two stochastically independent processes: a go process triggered by the go stimulus and a stop process triggered by the stop signal. If the stop process wins, participants will inhibit their response. On the other hand, when the go process wins, participants will respond. The race model allows to estimate an otherwise unobservable variable, the time necessary to react to the stop signal, the stop signal reaction time (SSRT; Logan 1994; see also Band et al. 2003).

The race model assumes that the go and the stop processes are stochastically independent, namely that the duration of two processes is not reciprocally correlated (Logan 1994; Band et al. 2003). However, stochastic independence does not exclude the possibility of a functional dependence. In fact it has been shown that a reduced response readiness

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independently affects both the reaction times (RT) and the SSRT (Van den Wildenberg et al. 2002), thus indicating that both the primary and the secondary task can be influenced by a common factor. Other studies reached the same conclusions. For instance, Kramer et al. (1994) and Ridderinkhof et al. (1999) showed that stopping is more difficult when a response conflict has to be resolved during the go process.

In this study, to further elucidate the relationship between the two competing processes, we sought to determine if and how a manipulation of the fixation target offset time, known to reduce the RT of the go process (namely the so-called ‘gap effect’) affects the SSRT of hand reaching movements. The ‘gap effect’, first described for eye movements, is one of the most studied factors in reducing RTs. Removing the central fixation spot 200 ms before the appearance of the peripheral target produces a remarkable decrease of saccadic RT (Saslow 1967; Fischer and Ramspurger 1984; Weber and Fischer 1995). The facilitatory ‘gap effect’ was attributed to combination of a general warning signal and of an oculomotor-specific facilitation (Kingstone and Klein 1993; Reuter-Lorenz et al. 1995; Pratt et al. 2000). In this frameset, the offset of the fixation spot would act as a warning of the forthcoming target and, at the same time, it would reduce the activity of fixation cells in the superior colliculus (SC) that maintains the eyes still on the fixation stimulus (Munoz and Wurtz 1993a, b). While there is no doubt about the role of the warning component in the reduction of saccadic RT (Reuter-Lorenz et al. 1995; Pratt et al. 2000), the role of the eyes fixation system might reflect the more general process of attentional shifts linked to movement preparation. In other words, this latter component of the ‘gap effect’ would not be specific to the oculomotor system, but it would represent the consequence of an attentional disengagement from the fixation spot, that occurs after its disappearance (Fischer 1987) being the first step in the sequence of events that bring to the execution of a movement (Posner 1980). The term ‘attentional disengagement’ refers to the process that removes selective attention from one target in favor of a novel target. This process is time-consuming (Posner and Petersen 1990) because it works against the strong inhibition that the fixation target exerts over all other potential targets. The temporal gap enables attention to be more easily disengaged before the novel target appears, thus inducing faster motor responses (Fischer and Weber 1993). This interpretation of the ‘gap effect’ can explain both the so-called ‘perceptual gap effect’, namely the improved performance in perceptual discrimination tasks when a time delay is introduced between the offset of the fixation and the go signal (Mackeben and Nakayama 1993; Pratt and Nghiem 2000; Song and Nakayama 2006) and the presence of a ‘gap effect’ in arm reaching movements (Bekkering et al. 1996; Gómez et al. 1995; Song and Nakayama 2006). The independence of the

‘gap effect’ for eye and arm movements was first demonstrated by Bekkering et al. (1996). They showed that a ‘gap effect’ occurred in a condition where subjects were required to produce aimed pointing movements, but were not allowed to move the eyes. Interestingly, in the same study, no ‘gap effect’ was found when the subjects were asked to perform not spatially oriented movements responses (e.g., when simple key presses were required).

According to the attentional account of the ‘gap effect’, we hypothesized that the timing of the central target offset in a countermanding reaching task (Mirabella et al. 2006a, 2008) should influence both the RT and the SSRT. In fact, the early disappearance of the central target would draw visual attention away from the center, advantaging the go process but increasing the time needed to react to a stop signal reappearing centrally. This hypothesis is in contrast with respect of two recent findings (Morein-Zamir and Kingstone 2006; Stevenson et al. 2007). In both those studies the influence of the fixation point removal during a countermanding task has been investigated for saccadic eye movements. Stevenson et al. (2007) introduced a 200 ms gap between the disappearance of the fixation point and the onset of the peripheral target, while in the study of Morein-Zamir and Kingstone (2006) the central target disappeared simultaneously to the peripheral target (0 ms gap). In both cases, the performance was compared with a version of the countermanding task where the central target remained on for the entire duration of the trial (overlap condition) and the stop signal was indicated either by an overlapping stimulus (Morein-Zamir and Kingstone 2006) or by a change in color of the central target (Stevenson et al. 2007). They found different results. Stevenson et al. (2007) found that the early removal of the fixation spot decreased the duration of the SSRT. On the other hand, Morein-Zamir and Kingstone (2006) did not find a relationship between the fixation offset and the length of the stop process.

However, since the saccadic system has a different functional organization (Munoz and Schall 2004) with respect to that controlling arm movements, we wanted to study the effect of introducing a gap epoch in a countermanding reaching task (Mirabella et al. 2006a, 2008). Following our hypothesis, the presence of a gap epoch should lengthen the SSRT of arm movements, i.e., the stop process should take more time, passing from a no-gap (0 ms gap) to a gap version (200 ms gap) of the countermanding task.

## Methods

### Participants

Ten right-handed university students (all female; age range 22–27) with normal or corrected to normal vision

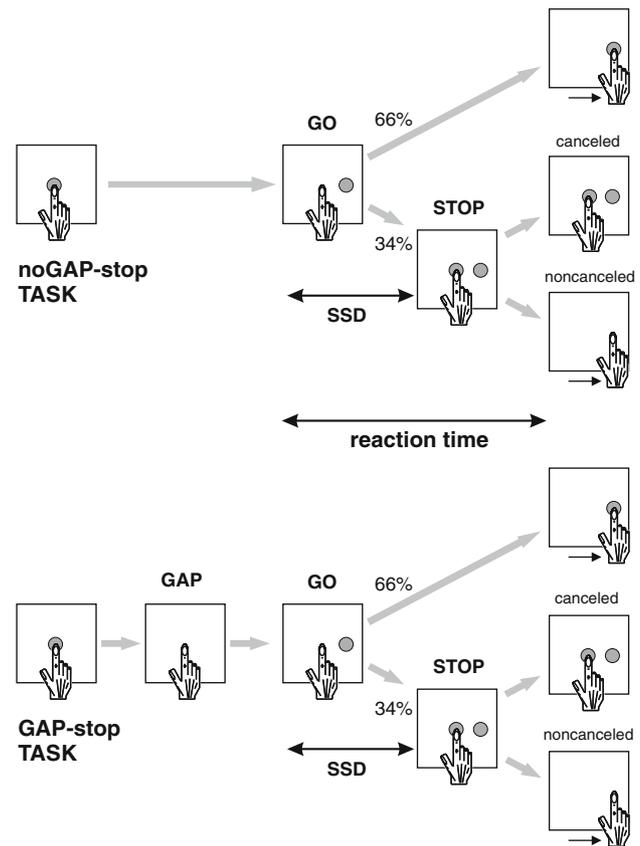
participated for course requirements and credits. All subjects gave their informed consent and experimental procedures were approved by the local ethics board and were in accordance with the ethical standard laid down in 1964 Declaration of Helsinki.

### Apparatus and task

Subjects seated in a darkened, sound attenuated chamber, with their head restrained by a chin rest so that their eyes were kept 40 cm away from a 17" PC monitor (CRT noninterlaced, refresh rate 85 Hz, 800 × 600 resolution, 32-bit color depth) on which visual stimuli, consisting of red circles (2.434 cd/m<sup>2</sup>) of 2.5° diameter against a dark background of uniform luminance (<0.01 cd/m<sup>2</sup>), were presented. The PC monitor was equipped with a touch screen (MicroTouch, sampling rate 200 Hz) for touch positions monitoring. A noncommercial software package, CORTEX (<http://www.cortex.salk.edu>), was used to control stimuli presentation and to collect behavioral responses.

Subjects performed, in separate blocks counterbalanced across participants, two different versions of the countermanding reaching tasks (Fig. 1; GAP-stop vs. noGAP-stop task). In both cases, the task consisted of a random mix of 66% no-stop and 34% stop trials. All trials began with the presentation of a central target and subjects had to maintain their right index on this position for a variable holding period (500–800 ms). Thereafter, the two tasks were different for the presence (GAP-stop task) or absence (noGAP-stop task) of a temporal gap (212 ms; 18 units of refresh rate) between the central target offset and the appearance (go signal) of the peripheral target. In no-stop trials, subjects were instructed to generate a speeded reaching movement toward the peripheral target, randomly presented either to the right or to the left at the same eccentricity (11.3°; 8 cm). Stop trials differed from no-stop trials because of the reappearance of the central target (stop signal) after a variable delay (SSD). Subjects were instructed to refrain from moving at the presentation of the stop signal. Stopping becomes increasingly more difficult with lengthening of the SSD. Trials in which subjects successfully withhold the movement were defined canceled trials, while those in which they moved were defined noncanceled trials. Successful trials were signaled by an acoustic feedback. Noncanceled trials were also signaled by the disappearance of both targets as soon as the movement started (Fig. 1).

We dynamically varied the duration of the SSDs using a staircase procedure (Levitt 1971) to keep the probability of failing to inhibit equal to the probability of successfully inhibiting the movement [i.e., a  $P(\text{failure})$  around 0.5]. More in detail, SSDs were increased/decreased by 2



**Fig. 1** Schematic of the task. Temporal sequence of the visual displays for noGAP-stop and GAP-stop paradigms. All trials began with the presentation of a central stimulus. After a variable holding, the two tasks were different for the presence (GAP-stop task) or absence (noGAP-stop task) of a temporal gap between the central target offset and the appearance (go signal) of the peripheral target. In the no-stop trials subjects had to perform a speeded reaching movement toward the peripheral target within a maximum time. On a fraction of interleaved trials (34%) the central stimulus (stop signal) reappeared after variable delays (SSDs), instructing the subject to inhibit movement initiation. On noncanceled trials the peripheral target was removed before movement completion for error feed-back to the subjects

(23.6 ms; 2 subjects) or 3 (35.3 ms; 8 subjects) units of refresh rate after each canceled/noncanceled trial. Since it is known that the RT of reaching movements depends on the spatial relationship between target position and arm employed (for a review, see Marzi et al. 1991) we used two independent staircase algorithms for updating SSDs toward right and left targets. To refrain subjects from slowing down their movements, a common strategy adopted in order to make easier the inhibition on stop trials, they were informed about the tracking procedure and that probability of stopping will approximate 50%, irrespective of whether they were postponing their response or not. To further refrain subjects from slowing down their movements, we set an upper RT limit. Whenever the RTs were longer than 500 ms, no-stop trials were aborted and therefore signaled as errors to the subjects.

After a few trials of familiarization with the apparatus, we delivered to each subject a block of 60 trials. In this block the initial SSD was always set to 105.8 ms for both target directions. After the completion of the block, we determined the SSD that was more likely to be close to the delay allowing a  $P(\text{failure})$  close to 0.5 on the basis of the mean value of last two runs (see “Behavioral data analysis”) and we used this value during the corresponding experimental sessions. Consequently the starting SSD varied across subjects and across tasks. On average the starting SSD for the GAP-stop task was of 115.2 (SE  $\pm$  9.1; range 82.3–176.4), while that for the noGAP-stop task was of 156.4 (SE  $\pm$  13.3; range 82.3–235.2).

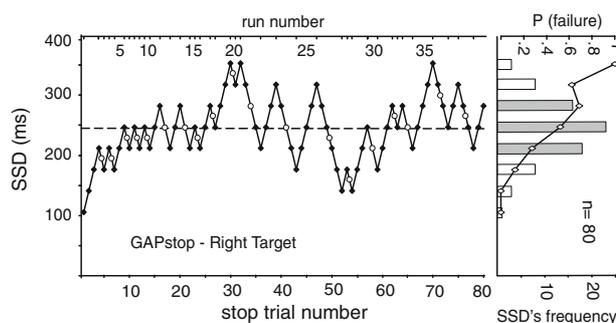
During the experimental session, each participant performed 480 trials (320 no-stop and 160 stop trials) for each version of the countermanding task.

### Behavioral data analysis

The use of the staircase algorithm provides a reliable SSRT estimate, since it is derived from the central part of the no-stop trials RT distribution and hence it is relatively insensitive to violations of the race model assumptions (Logan et al. 1997; see also Band et al. 2003 for more details).

To compute the SSRT for each staircase algorithm dataset we used two different procedures, both based on the assumption that the SSRT is a constant and that go process durations are roughly the same for no-stop and stop trials (integration method, Logan and Cowan 1984; see also Band et al. 2003). Using the integration method, the SSRT is obtained for a given SSD by subtracting the finishing time of the stop process for the starting time (the SSD value). The finishing time of the stop process is calculated by integrating the no-stop trials RT distribution from the onset of the go signal until the integral equals the corresponding observed proportion of noncanceled trials [ $P(\text{failure})$ ]; Logan 1994]. The two procedures differed for how a single SSRT value was obtained starting from the many SSDs available on each dataset.

In the first procedure, we worked out a ‘representative’ SSD, namely that delay that better corresponds to the time needed to the subject to withhold a response half of the times. As shown in Fig. 2 for an example case, the sequence of SSDs displays either runs of increasing values and runs of decreasing values according to the performance of the subject. We calculated the ‘representative SSD’ using the mid-run estimate method (Wetherill 1963, 1966; see also Levitt 1971 for a methodological discussion), which consists of averaging the values corresponding to the midpoint of every second run (Fig. 2, white dots). A ‘representative’ SSD was obtained for each task version and for each target location of each subject and used to compute the



**Fig. 2** Typical SSD sequence drawn from the performance of one example subject. The SSDs (*black diamonds*) continuously change according to the subject’s performance. A run consists of a sequence of changes in SSD duration in one direction (occurring either when a subject makes a series of correct or incorrect stop). The estimated ‘representative SSD’ (*dashed line*) is obtained by averaging the midpoint (*white dot*) of every second run in the sequence. This ‘representative SSD’ was used to compute the SSRT with the first procedure (see text for details). The probability of failure [ $P(\text{failure})$ ] is indicated in the right side of the plot for each SSD value (*white diamonds*). At the same time the numbers of SSD presented is reported as histogram. *Filled bars* indicate the SSDs presented more than ten times. These SSDs were those used to compute the SSRT with the second procedure (see text for details)

corresponding SSRT with the described integration method.

In the second procedure, we detected those SSDs that were presented at least ten times for each target location and for each task version of each subject (filled bars in the histogram for the example data of Fig. 2; for a similar approach see Logan et al. 1997). Using the described integration method, we computed the SSRT for each of the selected SSDs and, to obtain the second estimate of the SSRT, we average them out (Band et al. 2003). This method is not different in principle from that normally employed when the SSDs are varied in a factorial manner (i.e., randomly selected from a limited set of possible SSDs; Band et al. 2003).

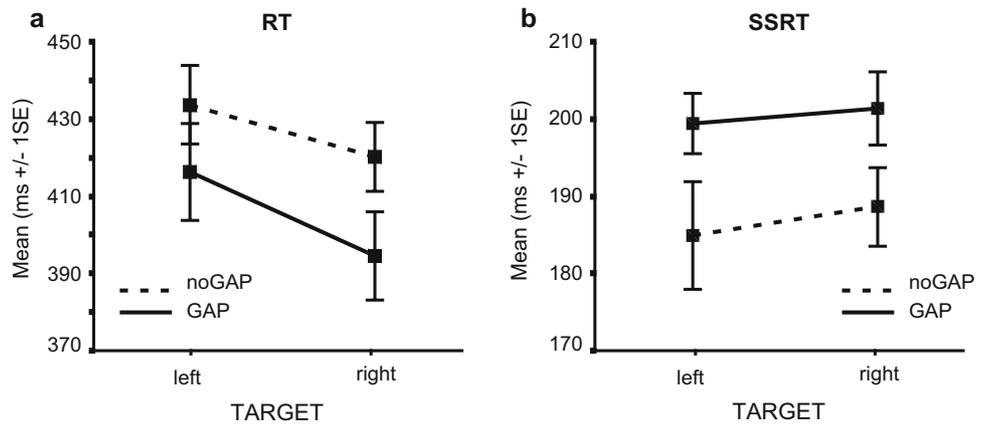
Since the two procedures yielded results not significantly different (see “Results”), we averaged them out to obtain the final estimated SSRT value for each combination of subject, task condition and target position.

## Results

### Reaction time of no-stop trials

Figure 3a and Table 1 show that a ‘gap effect’ for reaching arm movements emerged in the context of the countermanding task. A 2-way repeated measure ANOVA (factors: task condition and target position) showed that RT in the GAP-stop task were faster than RT in the noGAP-stop

**Fig. 3** Behavioral estimates. **a**, **b** Mean values ( $\pm$ SE) of no-stop trials reaction time (RT) and stop signal reaction time (SSRT) for either task used (GAP vs. no-GAP) and target position (*left* vs. *right*), respectively



**Table 1** Summary of behavioral and estimated values for the two tasks

	Left target	Right target
NoGAP-stop task		
No-stop trials RT	433.7 ( $\pm$ 10.1)	420.2 ( $\pm$ 8.8)
Noncanceled trials RT	400.7 ( $\pm$ 13.5)	379.9 ( $\pm$ 12.4)
$P$ (failure)	0.47 ( $\pm$ 0.01)	0.47 ( $\pm$ 0.01)
Representative SSD	244.65 ( $\pm$ 12.1)	228.85 ( $\pm$ 7.8)
SSRT	187.8 ( $\pm$ 6.4)	189.2 ( $\pm$ 5.5)
GAP-stop task		
No-stop trials RT	416.1 ( $\pm$ 12.5)	394.5 ( $\pm$ 11.4)
Noncanceled trials RT	376.7 ( $\pm$ 12.2)	348.9 ( $\pm$ 14.2)
$P$ (failure)	0.46 ( $\pm$ 0.01)	0.48 ( $\pm$ 0.001)
Representative SSD	210.15 ( $\pm$ 12.6)	191.22 ( $\pm$ 17.1)
SSRT	198.0 ( $\pm$ 4.1)	203.1 ( $\pm$ 5.0)
‘GAP effect’		
No-stop trials RT	17.6	25.7
Noncanceled trials RT	24.0	31.0
Representative SSD	34.5	37.6
SSRT	-19.2	-13.5

For each target position and across all tested subjects the table shows: mean RTs ( $\pm$ SE) of no-stop and noncanceled trials;  $P$ (failure) computed for the block; representative SSD ( $\pm$ SE) as computed using the procedure described in the methods; mean SSRT ( $\pm$ SE). For each value, the difference between the noGAP and GAP version of the task is presented as ‘gap effect’

version [ $F(1,9) = 11.31$ ,  $MSE = 414.3$ ,  $P < 0.01$ ]. No other significant effects were found [target position  $F(1,9) = 4.23$ ,  $MSE = 729.84$ ,  $P = 0.07$ ; interaction  $F(1,9) = 1.61$ ,  $MSE = 106.16$ ,  $P = 0.24$ ].

We looked for possible correlations between the RTs of no-stop trial obtained in the two task versions. RTs of no-stop trials in GAP and noGAP-stop tasks displayed a significant correlation for both target directions (target right:  $r = 0.86$ ,  $df = 8$ ,  $P < 0.005$ ; target left:  $r = 0.76$ ,  $df = 8$ ,  $P < 0.05$ ), meaning that subjects that were faster on one task were faster even in the other.

### Estimate of SSRT

First of all we computed, separately for each task, the average proportion of noncanceled trials [ $P$ (failure); Table 1] obtained with the two staircase tracking algorithms. A 2-way repeated measure ANOVA with task conditions (GAP vs. noGAP) and target position (right vs. left) as factors, revealed the absence of any significant effect [condition:  $F(1,9) = 0.81$ ,  $MSE = 0.00$ ,  $P = 0.39$ ; target position:  $F(1,9) = 4.16$ ,  $MSE = 0.00$ ,  $P = 0.07$ ; interaction:  $F(1,9) = 0.83$ ,  $MSE = 0.00$ ,  $P = 0.39$ ] on the different  $P$ (failure) values obtained. The average  $P$ (failure) across all conditions was of 0.47 ( $SE = \pm 0.6$ ). Therefore, both the staircase algorithms produced a similar behavior outcome across all task conditions and target locations.

A necessary condition for obtaining a reliable estimate of the SSRT, is to satisfy the basic assumption of the race model, that is the stochastic independence between the go process (the process initiated by the go signal leading to the execution of the movement) and the stop process (the process initiated by the stop signal leading to the inhibition of the movement). A way to test whether our data fit the model is to assess if the RTs of noncanceled trials were faster than those of no-stop trials (Logan and Cowan 1984; Logan 1994). As shown in Table 1, on average the noncanceled trials were always faster than no-stop trials (paired  $t$  test;  $df = 9$ ;  $P_s < 0.001$ ). Furthermore, for each subject, for each task condition and for each target position, we compared the distribution of RTs of noncanceled versus RTs of no-stop trials using a Kolmogorov–Smirnov test. In all occurrences but four (36/40; 90%) the prediction was fulfilled ( $P_s < 0.05$ ). Taken together, these results indicate that our data allowed a good estimate of the SSRT.

For each countermanding task version and target position, the SSRTs obtained with the two procedures (see ‘Methods’) were not significantly different (paired  $t$  test,  $df = 9$ ,  $P_s > 0.05$ ). As in other studies (Hanes et al. 1998; Paré and Hanes 2003), we averaged them out to obtain a

single SSRT value. Then, in order to compare the SSRT obtained in the noGAP-stop task to that obtained in the GAP-stop version (Fig. 3b; Table 1), we performed a 2-way (factors: task condition and target position) repeated measure ANOVA. The result showed that SSRT in noGAP-stop task were shorter than SSRT in GAP-stop task [condition:  $F(1,9) = 5.38$ ,  $P < 0.05$ ; position:  $F(1,9) = 0.33$ ,  $P = 0.58$ ; interaction:  $F(1,9) = 0.02$ ,  $P = 0.89$ ]. Hence, in agreement with our initial hypothesis, the presence of a temporal gap between the onset of the go signal and the presentation of the peripheral target speeds up the RTs of reaching arm movements, but at the same time it slows down the latency of the inhibitory processes.

Several arguments are in favor of the independence of the two effects. First of all, it must be considered that the staircase procedure was used to filter out the effect of the go process facilitation from the race outcome. Since a  $P$ (failure) close to 0.5 was obtained independently from the RT decreases (see Table 1), we believe that the staircase procedure was successful. Moreover, the shortening of no-stop trials RT (namely the ‘gap effect’) was smaller (see Table 1) than the shortening of the ‘representative SSD’ required by the tracking algorithm to maintain a  $P$ (failure) close to 0.5 when passing from the noGAP to the GAP version of the task [2-way repeated measure ANOVA; factors: shortening effect and target position; shortening effect:  $F(1,9) = 6.54$ ,  $P < 0.05$ ; position:  $F(1,9) = 0.32$ ,  $P = 0.59$ ; interaction:  $F(1,9) = 0.23$ ,  $P = 0.64$ ]. Finally, we looked, across subjects, for possible correlations, within each condition, between no-stop trials RTs and the corresponding SSRTs. None of the four comparisons reached significance (GAP-stop task: right target, Pearson =  $-0.57$ ,  $P = 0.08$ ; left target, Pearson =  $0.41$ ,  $P = 0.24$ ; noGAP-stop task: right target, Pearson =  $-0.52$ ,  $P = 0.12$ ; left target, Pearson =  $-0.21$ ,  $P = 0.55$ ).

Overall, these data support the assumption of independence between stop and go process and allow us to discard the possibility that the increased duration of the SSRT in the GAP task was simply the result of a decrease of RTs of no-stop trials in the same task.

## Discussion

### The ‘gap effect’ for arm response

The present study confirms the presence of the gap effect for spatially oriented arm movements (Bekkering et al. 1996; Pratt et al. 1999; Song and Nakayama 2006) extending the finding to reaching movements performed in the context of the countermanding paradigm. By comparing the average RTs of no-stop trials in the noGAP-stop task, where the offset of the central target was simultaneous to

the onset of the peripheral target, with those in the GAP-stop task, where the central target disappeared about 200 ms before the onset of the peripheral target, we found that on average the RTs of the latter were about 20 ms faster.

In the present experiment, we cannot fully distinguish between an attentional and a generic warning component of the ‘gap effect’. However, three lines of evidence support an explanation in terms of attention. First of all, the magnitude of the ‘gap effect’ is similar to that previously reported for both arm and hand movements in studies where the warning effect was subtracted (Bekkering et al. 1996; Pratt et al. 1999; Song and Nakayama 2006). Second, in our experimental design the general warning effect, provided by the central target disappearance, was present during no-stop trials of both noGAP-stop and GAP-stop conditions. Third, the warning component has been functional associated to response readiness (Kingstone and Klein 1993; Paré and Munoz 1996). Two studies manipulated the state of readiness during a countermanding key-press task (van den Wildenberg et al. 2002, 2003), finding that whenever response readiness was reduced both RT and SSRT were increased. However, our approach does not give a definitive answer with respect to those studies (Reuter-Lorenz et al. 1995; Pratt et al. 2000) where the warning component of the ‘gap effect’ was fully explored employing both an anticipatory acoustic signal and an overlap condition, namely a condition where the central target remains on and overlaps with target presentation.

Similarly, several lines of evidence suggest that the arm ‘gap effect’ we found it is unlikely to be simply due to a low-level fixation offset effect (FOE). First of all, in our experimental design, the central target disappeared during both GAP and noGAP-stop task conditions, therefore a FOE effect should be present in either case. Second, most of the FOE has been ascribed to the functional organization of the intermediate layers of the SC (Kingstone and Klein 1993; Reuter-Lorenz et al. 1995; Pratt et al. 2000) where reaching related neurons have been also described (Werner et al. 1997; Stuphorn et al. 1999). However, a ‘gap related activity’ has not been described for SC’s reaching neurons and the pattern of discharge of eye fixation neurons during arm movement production (Lünenburger et al. 2001) is different from that described during saccadic eye movements (Munoz and Wurtz 1993a, b). Finally, it had been shown that processes underlying the ‘gap effect’ are modulated by mechanisms that affect the allocation of spatial attention (Pratt and Nghiem 2000; Pratt et al. 2006). These and other findings (Machado and Rafal 2000) support the idea that cognitive factors, such as the behavioral strategy of the subject, can influence the ‘gap effect’.

## The ‘gap effect’ for arm response inhibition

This study has shown, for the first time, that the presence of a temporal gap between fixation point offset and target presentation increases the duration of SSRT for reaching arm movements.

At odd with our results, using a similar experimental design, Morein-Zamir and Kingstone (2006) failed to find an effect of fixation offset for saccadic SSRT. There are several possible accounts to explain this discrepancy. A straightforward possibility is that we studied reaching movements while they focused on saccadic movements and the two motor systems might be controlled differently. Another simple explanation lies in the fact that they compared an overlap versus a noGAP condition. However, we are in favor of a third possibility. In the experiment of Morein-Zamir and Kingstone (2006), in both experimental conditions, four white points forming a square around the fixation spot were displayed for the entire duration of the trial with the purpose of helping the subjects to maintain fixation despite the lack of a central visual stimulus. This procedure reduced the ‘gap effect’ found. Noteworthy, even though they found a significant ‘gap effect’ on saccadic RTs, its size was rather small, about 10 ms, while other studies, e.g., Pratt et al. (2000), reported a decrease of about 70 ms in the RTs of gap trials for saccadic eye movements. In conclusion, our argument is that the experimental protocol used by Morein-Zamir and Kingstone (2006) failed to efficiently favor the shift of attention from the fixation point toward the target and, therefore, the anticipated offset of the fixation point was less capable to influence negatively the response to the stop signal.

Another work studied the effect of introducing a gap period in a countermanding saccade task (Stevenson et al. 2007). By comparing overlap and GAP conditions, the authors observed a decrease of SSRT in the latter condition regardless of the stop signal modality (which could be either a visual or acoustic). Bearing in mind that we did not have an overlap condition in our experimental setting, the results of Stevenson et al. (2007) contrasts with ours. As suggested before, the discrepancy in the results could be accounted for by the independence between eye and hand movement control systems. At least in the context of the countermanding task, two studies provided evidence in favor of this hypothesis (Logan and Irwin 2000; Boucher et al. 2007a, b). Logan and Irwin (2000) compared inhibitory control of eye and hand movements by asking subjects to withhold/execute either saccadic eye movements or hand key presses. They found that the SSRT for saccades was faster than that for hand key presses, but more importantly experimental conditions affected differently the stopping times of saccades and hand key presses. These results are consistent with the idea that hand and eye motor systems

are inhibited by different processes obeying similar principles. Boucher et al. (2007a, b) reached the same conclusions. In their experiment they asked participants to perform a countermanding task where the effector (eye only, hand only or eye and hand) to be used was defined by an instruction at the beginning of each trial. The stop signal could be presented either in a visual or in an acoustic modality. Regardless of the nature of the stop signal, the authors confirmed that SSRT duration was longer for hand than for eye movements (even for coordinated eye/hand movements). Moreover, they showed that knowing in advance which effector one had to stop did not alter the SSRT duration. Finally they found that the SSRT for hand movements did not change according to whether the eye must be stopped or not.

In conclusion, data in the current literature show that a strong interaction between the systems responsible for canceling eye and hand movements is very unlikely (Boucher et al. 2007a, b). In this respect, we believe that the lack of eye monitoring in our study does not limit the interpretation of our data. However, recording eye positions during reaching countermanding task can surely be of interest because of the well known link between the effectors (Land et al. 1999; Hayhoe et al. 2003).

Another important finding of our study must be considered. Even though the perceptual gap had an influence on both movement generation and inhibition, our results clearly support the assumption of stochastic independence between stop and go processes. In fact, the main predictions of the race model (Logan and Cowan 1984) were satisfied and there was no correlation between the average RT values of no-stop trials and the corresponding average SSRT values. Therefore the temporal gap independently affected the go and the stop processes. We believe that the opposite effect observed might be explained by the disengagement of visual spatial attention from the central target in the GAP-stop task (Fischer and Breitmeyer 1987; Fischer and Weber 1993). Successful performance in the stop trials requires a constant monitoring of the appearance of the stop signal that, in our study, could appear at the center of the screen. It is possible that the disengagement of the attention from the central target, due to the gap, facilitated the reaction to the peripheral target at the same time slowed down the response to the stop signal. In this respect, it would be interesting to investigate the ‘gap effect’ on SSRT when stop signals are presented at the target’s spatial location. So far the effect of the stop signal location was studied only in saccadic countermanding task without gap manipulation (Asrress and Carpenter 2001). These authors showed that central and peripheral stop signals acted independently but with equal effectiveness, that is the SSRT was not different in the two conditions. On this ground, we speculate that the gap epoch in the countermanding reaching task could

positively influence the stop efficacy if the stop signal would not be presented at the center of screen, but instead at a position spatially coincident or close to target location. In this instance, the favored shift of spatial attention toward target location should correspond to a lower cost for responding to the stop signal. In this instance we would therefore expect to find shorter SSRT for GAP-stop task.

#### Functional link between selective attention and motor suppression

Executive functions represent a set of processes that include selective attention and inhibitory control (Sergeant et al. 2002; Stuss et al. 1995). Congruent responses depend on the coordination of both attentional mechanisms for target selection and mechanisms for inhibiting inappropriate responses. An inappropriate response could be the result of either an increased distractibility (attention deficit) or a failure to inhibit the wrong response.

Several experimental evidences support the presence of a link between selective attention and motor control. This link has been easily proposed for oculomotor control. Neuroimaging and neurophysiological studies have demonstrated that saccadic eye movements and covert attention allocation activate a common network of brain regions (see Corbetta et al. 1998; Schall and Thompson 1999, for reviews). Furthermore, behavioral studies showed that the locus of attention affects the trajectory of saccades (Sheliga et al. 1995).

The modulation of selective attention during manual response preparation had been more difficult to demonstrate. However, in the last years supports to this view are rapidly accumulating. Deubel et al. (1998) and Schiegg et al. (2003) have demonstrated that subjects have superior visual discrimination performance for locations close to the target of goal-directed manual movements. In line with these results, Eimer et al. (2006) showed that the N1 component of event-related brain potentials is enhanced whenever a task-irrelevant visual probe is presented close to the cue used for indicating the direction of a future reaching or saccadic movement. Song and Nakayama (2006), manipulating perceptual features of an odd-colored target search task, showed a reduction of the duration of manual pointing movements and a change of hand trajectories as the number of distractors increases. Since the same paradigm had been shown to facilitate the deployment of selective attention to a target (Bravo and Nakayama 1992), this support the idea that selective attention is a necessary ingredient of hand pointing actions.

Fischer and colleagues (Fischer and Breitmeyer 1987; Fischer and Weber 1993) first suggested that an important component of the gap effect is given by the disengagement of the visual spatial attention from the fixation spot, that automatically occurs after its disappearance and facilitates the generation of the motor response (see also Song and

Nakayama 2007). A similar mechanism could explain the slowing down of the stopping process, interpreted as the capacity to fast react to stop signal presentation, observed in our study. In fact, it is highly probable that when the stop signal appears at the center of the screen during stop trials of the GAP-stop task, spatial selective attention is already disengaged from the central location and its reallocation has a time cost. Therefore, the amount of time needed to react to the stop signal will be longer because of the need of reorienting the attentional focus. These observations are in agreement with results reported for ADHD patients tested in the countermanding task. These patients are facilitated to respond to the target in the no-stop trials when compared to normal subjects, because of their well known impulsivity, at the same time this 'advantage' corresponds to a cost for stop signal response, in fact they display a longer SSRT when compared to normal age and sex matched participants (Armstrong and Munoz 2003; Schachar et al. 2000).

In conclusion, our results suggest the existence of a link between selective attention and both motor generation and suppression.

#### Neural bases of motor suppression for arm movements

Multiple lines of evidence suggest that successful inhibition of hand movements is due to the action of a fronto-basal-ganglia-thalamic pathway on the motor regions of the cortex (Aron 2007). Two areas of the frontal cortex, the inferior frontal cortex (IFC) and pre-SMA have been particularly investigated. While a key role has been initially proposed for the IFC (Aron et al. 2003; Aron and Poldrack 2006; van den Wildenberg et al. 2006; Chambers et al. 2006; Iversen and Mishkin 1970; Sasaki et al. 1989; Saka-gami et al. 2001; Aron et al. 2007) recent data have suggested an important role for the functionally interconnected pre-SMA area (Aron et al. 2007, Floden and Stuss 2006; Nachev et al. 2007; Isoda and Hikosaka 2007). Both areas could modulate the cortical neural processes for movement initiation via the hyperdirect route, passing through the sub-thalamic nucleus (Mink 2003; Nambu et al. 2002; Aron and Poldrack 2006; Aron et al. 2007).

In humans, the primary motor cortex (M1) has been proposed to play a direct role on motor suppression. A transcranial magnetic stimulation (TMS) study showed that stimuli applied over M1 during stop trials compared to those applied during no-stop trials induced both an increase in short-interval intracortical inhibition as well as a decrease in cortical spinal excitability (Coxon et al. 2006). Similarly, event-related potentials recordings have shown a decrease in the lateralized readiness potential (LRP), related to motor cortex activity, in both inhibited and partial inhibited movements with respect to executed movements (van Boxtel et al. 2001).

Despite these findings, the neural mechanisms at the basis of the suppression of a pending arm movement are still not well understood. Single unit neural activity related to inhibitory control of arm movement has been found both in M1 (Miller et al. 1992; Port et al. 2001) and in the dorsal premotor cortex (PMd; Kalaska and Crammond 1995) in monkeys performing Go/No-Go paradigms. However, there is an important difference between the Go/No-Go task and the countermanding task. In the former it is a potential movement that has to be inhibited while in the latter it is an ongoing response that has to be suppressed. A recent report (Mirabella et al. 2006b) showed that activity of single PMd neurons of monkeys performing a countermanding task, significantly changes when a movement is executed with respect to when a movement is inhibited before the SSRT has elapsed. The putative role of PMd in motor suppression agrees with the results of lesion studies in both humans (Picton et al. 2007) and monkeys (Moll and Kuypers 1977).

The neural basis of motor suppression for saccadic eye movements has been described better. In the oculomotor centers, frontal eye field (FEF) and SC, stopping eye movements is associated with both a decrease of neural activity of movement neurons and an increase of activity in the fixation neurons (Hanes et al. 1998; Paré and Hanes 2003; Boucher et al. 2007a, b). The fronto-basal-ganglia-thalamic pathway is potentially able to act directly on this functional organization (Matsumara et al. 1992; Isoda and Hikosaka 2007).

It is known that both M1 and PMd are involved in arm movement preparation showing neural activity related to both the specification of movement parameters and RT changes (Weinrich and Wise 1982; Riehle and Requin 1993; Riehle et al. 1994). Furthermore, both areas have direct projection to the spinal cord (Dum and Strick 2002). Their functional relation with arm movement initiation (see also Lecas et al. 1986) is similar to that described in both FEF and SC during saccadic eye movement generation (Munoz and Schall 2004). Therefore, even if a fixation/movement organization has not been described neither for M1 or PMd, we hypothesize that the neural network devoted to arm motor suppression might be organized similarly to that involved in saccadic suppression (Hanes et al. 1998; Paré and Hanes 2003). However, more studies are necessary to delineate their specific role.

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