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RESEARCH ARTICLE

Unilateral reaction time task is delayed during contralateral movements

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Abstract Performing unlearned unimanual tasks when simultaneously carrying out another task with the contralateral hand is known to be difficult. The dual task interference theory predicts that reaction time will be delayed if the investigated task is performed in the course of ongoing contralateral movements. Ballistic movements can be performed at maximal speed in simple reaction time (SRT) experiments when subjects have adequately prepared the motor system needed for movement execution. When fully prepared, activation of subcortical motor pathways by a startling auditory stimulus (SAS) triggers the whole reaction. In this study, we have examined dual task interference with reaction time in eight healthy volunteers. They were presented with a visual imperative signal to perform unilateral SRT either in a baseline condition (control trials) or while carrying out contralateral rhythmic oscillatory movements (test trials). A SAS was introduced in 25% of the trials in both conditions. SRT was significantly delayed in the interference test trial when compared to control trials either with or without SAS ($P < 0.001$). Control and test trials with SAS were significantly faster than those without SAS in both conditions ($P < 0.001$). However, there were no significant differences in the percentage SRT shortening induced by SAS or in the percentage SRT delay observed in the test trials. Our results suggest that performing rhythmic oscillatory movements with one limb slows SRT in the contralateral limb and that this effect is likely related to motor preparation changes. The effect described here can be of interest for physiological studies of interlimb coordination and the mechanisms underlying the dual task interference phenomenon.

Keywords Ballistic movement · Dual task interference · Motor preparation · Startling auditory stimulus

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Introduction

Attempting to perform a unimanual task when simultaneously carrying out voluntary movements with the contralateral hand is a useful paradigm for the study of the dual task interference effect (Pashler 1994; Herath et al. 2001). In such conditions, the performance of one of the actions is typically impaired (Geurts et al. 1991; Lundin-Olsson et al. 1997; Mulder et al. 2002; Kumru et al. 2004; Jiang 2004). One example of dual task interference is the transient alteration of unilateral rhythmic oscillatory movements by performing a contralateral ballistic movement (Kumru et al. 2004). The opposite effects, i.e. those of rhythmic movements on the speed of a unilateral ballistic movement in a simple reaction time task paradigm (SRT), have been studied only scarcely (Buenaventura and Sarkin 1996; Castellote et al. 2004).

The physiological mechanisms underlying dual task interference are not completely understood. Executing a motor plan may involve issuing inhibitory commands to motor structures not involved in the voluntary action (Gerloff et al. 1998; Kumru et al. 2004; Gorsler et al. 2004). Alternatively, dual task interference may be an expression of a central bottleneck process for response selection or task execution (Pashler 1994; Lien and Proctor 2002; Muller et al. 2004; Ulrich et al. 2006). If one of the actions involves reacting to a sensory signal, factors involving the sensory system have to be taken into account, including divided attention (Sakai et al. 2000; Herath et al. 2001; Fernandes et al. 2006). Probably, many mechanisms simultaneously contribute to dual task interference with varying degrees depending on the specific experimental paradigm.

Our main objective in the study presented here has been to investigate whether performance of a voluntary movement prevents subcortical motor structures from reaching the required degree of preparation for fast execution of a ballistic movement. The amount of motor preparation reached before perception of the imperative signal (IS) directly correlates with the speed of the reaction in SRT paradigms (Henderson and Dittrich 1998; Carlsen et al. 2006). One method to measure the excitability enhancement occurring in subcortical motor structures before movement execution is the StartReact effect, i.e. the subcortical triggering of a motor task when a startling auditory stimulus (SAS) is presented to a subject who is highly prepared to execute that motor task (Valls-Solé et al. 1999; Kumru and Valls-Sole 2006; Kumru et al. 2006; Carlsen et al. 2006). Therefore, we sought to improve our understanding of physiological mechanisms of motor control and, specifically, of some of the mechanisms underlying the dual task interference effect by studying how unilateral oscillatory movements affect contralateral SRT, the StartReact effect or both.

Methods

The study was carried out in eight healthy subjects, five men and three women, aged 25–35 years. Seven subjects were right handed and one was left handed. We included no persons with known bimanual skills such as musicians or artists. All subjects gave written informed consent for the study, which was approved by our local Ethics committee.

Stimulation and recording

Subjects faced a 14-inch computer monitor, situated at approximately 50 cm before the subjects' eyes. They were requested to react to a visual cue appearing in the computer's monitor. A 1 cm × 1 cm white cross was presented in the centre of an otherwise black screen, serving as the forewarning for the IS and as a gaze fixation point. The IS was a 5 cm × 5 cm that appeared after a variable period between 500 and 1,500 ms. One second after the appearance of the small cross on the computer screen, a pulse was generated by the computer to trigger the electromyograph (Neuropack 8, Nihon-Kohden, London).

A lineal accelerometer (model 348720; Bionic Ibérica S.A., Barcelona, Spain) was placed on the dorsum of each hand in the best position to record wrist oscillations and its changes before and during the tasks. The accelerometer recordings were low-pass filtered (0.1–10 Hz), digitized at a sampling rate of 200 Hz and stored on a personal computer equipped with the software package Acknowledge MP100 (Biopac Systems, Bionic Ibérica S.A., Barcelona). Individual recordings were classified according to condition for off-line analysis.

Startling auditory stimulus, applied in some trials as described under Sect. 'Experimental procedure', was produced by discharging the coil from a magnetic stimulator over a metallic platform. This produced a sound of an intensity of 130 dB sound pressure level, measured at a distance of 1 m from the source with a Brüel and Kjaer Impulse Precision Sound Level Meter type 2204. Such a procedure has been shown to be effective in inducing a startle reaction in most healthy subjects (Valls-Solé et al. 1999).

Experimental procedure

The subjects were sitting on a chair with their elbows supported by armrests and their hands relaxed and outstretched on top of a conveniently placed wooden surface, at approximately 30 cm distance from each other and 15 cm away from a 2 cm^2 button. They received full verbal instructions of the experiment. All trials began by asking the subject to pay attention to the computer's monitor and be ready to react. The task was to hit the button as fast as possible at the perception of the IS. The procedure involved two experimental conditions presented in a random order:

1. In the control condition, the subjects were requested to keep their hands in the resting position, on top of the wooden surface, until they performed the reaction.
2. In the test condition, subjects were requested to perform tremor-like rhythmic unilateral oscillatory wrist movements and carry out the same task as described above with the contralateral hand. We did not specify frequency or amplitude of the oscillatory movement, but requested to perform a smooth, consistent and rhythmic but comfortable wrist oscillation of more than 3 Hz, which could be maintained for extended periods of time.

Left and right hands were examined in a random order. For each condition, we collected a total of 20 trials for each hand. In 15 of them, we presented just the IS, while in the other five we presented the IS together with a SAS. The five trials containing SAS were intermingled with those containing no SAS in a random order. Additionally, we presented sham trials in which SAS was delivered while the subjects were either at rest or imitating tremor, but had not received any instructions regarding preparation for a reaction (no verbal commands for readiness, warning signal or IS). Two sham trials were presented for each condition. The subjects were allowed to practice to feel comfortable with the task. Trials were rejected on-line and repeated if subjects reacted before the IS or reacted late because of self-reported lack of attention.

Data reduction and analysis

We recorded periods of 4 s, which included 1,000 ms preceding the IS. We performed off-line analysis of the mean dominant frequency of the tremor-like oscillation in the pre-IS period using the Fast Fourier transform. Reaction time was measured as the latency in ms between the IS and the onset of accelerometric signal displacement in the reacting hand. Data for each condition were grouped for control and test trials with and without SAS. Therefore, we ended up with four groups of data: control trials with no SAS, control trials with SAS, test trials with no SAS and test trials with SAS.

For descriptive purposes, we calculated the mean and standard deviation values for each group of data. The individual's mean in the control trials with no SAS was assigned 100% and data for each trial in all groups were expressed as percentages. We used a two-factor ANOVA, one factor being the experimental condition (control vs test) and the other factor the presence or absence of SAS. Bonferroni's test was used for post-hoc analysis when significant differences were found. The Student's *t*-test was used for comparison of data from both sides. The level of statistical significance was set at $P < 0.05$.

Results

The experiments were completed without any difficulty by all subjects. The total duration of the experiment was about 1 h. There were no statistically significant differences in SRT in the control trials without SAS between the dominant and non-dominant hand (dominant hand 170.5 ± 12.1 ms; non-dominant hand: 172.1 ± 9.9 ms; *t*-test; P = 0.07). Therefore, we pooled data from both hands for further statistical comparisons.

In the test trials without SAS, the mean frequency of the oscillatory movement in the pre-IS period was 5.6 ± 0.5. As expected (Kumru et al. 2004), performing the ballistic reaction markedly modified the rhythmicity and consistency of the oscillations. The effect was variable among subjects, although all showed an amplitude decrement or transient stop of the oscillations in the majority of trials, with a mean latency of 138 ms (SD = 71 ms) and a mean duration of 314 ms (SD = 114 ms).

Startling auditory stimulus delivered at rest induced a slight wrist flexion movement in some subjects at a mean latency of 109 ms (SD = 21 ms). This was induced by the first SAS in almost all subjects and by the second SAS in only three subjects. When subjects were performing oscillatory movements to imitate tremor, the first SAS caused a slight decrease in the amplitude of the oscillatory movement (ranging from 8 to 18% of the initial amplitude) in some trials in five subjects. Neither any stop nor any other relevant change was induced by the second SAS in any of the subjects of our study.

The individual mean reaction time changes are depicted in Fig. 1 for the control and test trials with and without SAS. Table 1 shows the mean reaction time in absolute values and in percentage for the two conditions and the two types of trials. Statistical comparisons showed a significant effect of type of trial (ANOVA; $F = 146.3$; $P < 0.001$) and condition (ANOVA; $F = 46.4$; $P < 0.001$), but interaction between the two factors was not significant. The reaction time in the test trials was longer than that in the control trials, either with or without SAS. The mean percentage shortening induced by SAS was not significantly different when comparing control with test trials (66.6 ± 9.1% in control trials and 65.8 ± 10.2% in test trials). The percentage SRT lengthening induced by performing contralateral oscillatory movements was not significantly different when comparing trials with no SAS (124.9 ± 8.2%) and trials with SAS (126.5 ± 7.1%). Figure 2 shows examples of recordings from a representative subject for all four types of trials.

Discussion

There are two main results of our study: 1. Unilateral SRT is delayed when subjects perform oscillatory movements with the contralateral hand in comparison with the same task performed when subjects are at rest. 2. This effect occurs to a similar extent when SRT is speeded up in the context of a StartReact paradigm.

Delayed reaction time when performing contralateral oscillatory movements

It is common to experience difficulties when performing spatially or temporally differentiated tasks with both hands simultaneously (Buenaventura and Sarkin 1996; Klingberg and Roland 1997; Hazeltine et al. 2006; Matthews et al.

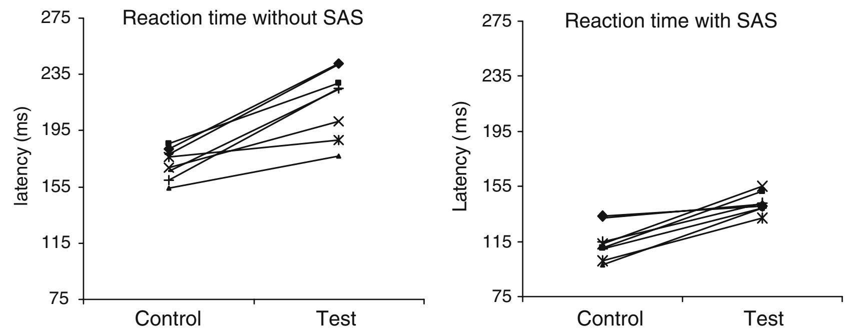

Fig. 1 Individual reaction time for each subject in both experimental conditions. Control: reaction time at rest (baseline condition). Test: reaction time during contralateral rhythmic oscillatory hand movements. *SAS*: startling acoustic stimulus

Table 1 Mean values of reaction time (standard deviation)

	Control-SRT (ms)	Test-SRT (ms)	Control-SRT (%)	Test-SRT (%)
No SAS	171.3 (11.0)	216.7 (24.8)	100.0 (6.4)	126.5 (11.4)
SAS	114.1 (12.3)	142.6 (7.6)	66.6 (10.8)	83.2 (5.3)

Values are the mean and one standard deviation (within parenthesis) for control and test trials with and without SAS. Values are given in ms and in percentage of the mean control trials. The percentage shortening of test trials with SAS compared to test trials without SAS is 65.8%

2006). This dual task interference has been used to demonstrate subtle motor dysfunctions in clinical practice, which have sometimes been reported with attractive names (Lundin-Olsson et al. 1997; de Hoon et al. 2003; Andersson et al. 2003; Hyndman and Ashburn 2004; Rochester et al. 2004; Hein et al. 2005). In an extensive review, Pashler (1994) reported delayed reaction time in the second task of a pair given in sequence, with a more marked delay when tasks had to be performed within short intervals. Surprisingly, however, unilateral SRT has been only scarcely considered as a probe for the interference effects. Buenaventura and Sarkin (1996) reported a delay in SRT when tapping with the contralateral hand, and Castellote et al. (2004) showed that unilateral SRT is also delayed when subjects perform their task on a background of ongoing slow oscillatory movements.

The physiological mechanisms underlying dual task interference in the context of SRT are not completely understood. Classically, a collision in perceptual processing of stimuli rather than impairment of motor preparation has been proposed. Recently, however, Obhi and Goodale (2005) showed evidence that interference occurs not only in stimulus processing, but also in motor preparation. Our findings suggest that there is indeed a lack of sufficient preparation within motor systems that could account for the delay in the execution of a motor task when performing oscillatory contralateral hand movements.

Excitability changes in cortical motor areas could provide an explanation for the findings of our study. Several authors have demonstrated an enhancement in the excitability of motor systems before and during the execution of a voluntary movement (Gerloff et al. 1998; Stinear et al. 2001; Sohn et al. 2003; McMillan et al. 2006). Excitability changes occur also in muscles not involved in the voluntary movement, with enhancement reported by some authors

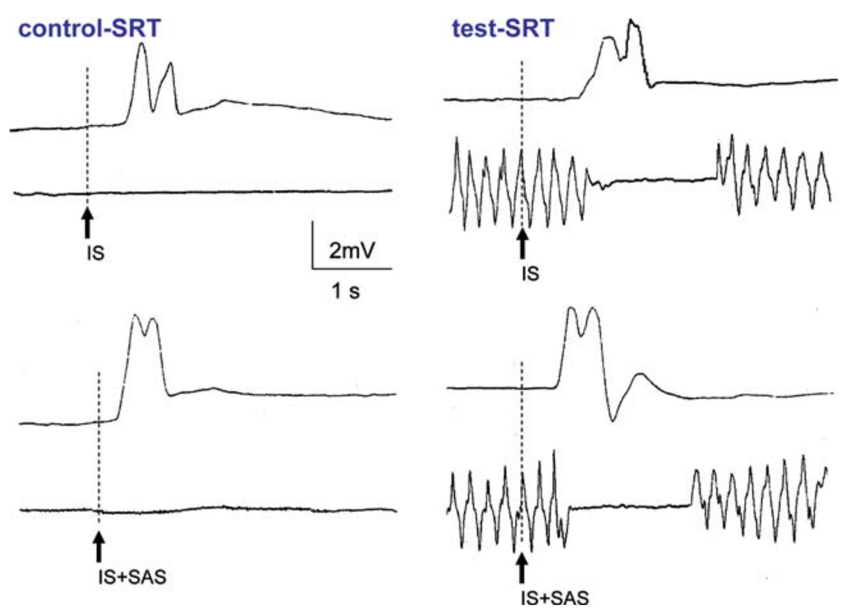

Fig. 2 Selected recordings from a representative subject reacting with the right hand in control (*left*) and test (*right*) conditions. Trials with no SAS are displayed at the *top* of the figure, and those with SAS are displayed at the *bottom*. *IS* imperative signal, *SAS* startling acoustic stimulus

examining tonic contraction of homologous muscles (Stinear et al. 2001) and inhibition reported by authors examining phasic muscle contraction (Gerloff et al. 1998; Sohn et al. 2003). Our finding of a delay of test SRT compared to control SRT fits well with the observations reported by Sohn et al. (2003), who showed that phasic contraction of the first dorsal interosseous muscle caused inhibition of motor-evoked potentials elicited by single pulse TMS on the contralateral hand. Inhibition was not only directed towards the homologous muscles, but also involved a more diffuse area (Sohn et al. 2003). The degree of inhibition was larger for the distal and adjacent muscles than for the homologous and proximal muscles.

Divided attention, which is intrinsic to the execution of separated simultaneous bimanual tasks, can also provide an explanation for the interference effects reported here. Considering the fact that performance is better with attention to the task, it is not surprising that it gets worse when attention needs to be divided. Other studies also confirmed the role of divided attention in movement constraints (Herath et al. 2001; Mulder et al. 2002; Jiang 2004; Fernandes et al. 2006; Catena et al. 2007). Learning a new motor task is associated with progressive automatisms and reduced participation of cognitive areas of the brain (Puttemans et al. 2005). Mulder et al. (2002) showed that motor control of a task is most efficient when less cognitive involvement is needed. The more cognitive involvement is required in a task, the larger the interference produced by a concurrent attention-demanding task. Swinnen and Wenderoth (2004) showed that, when performing bimanual hand movements, the motor action is easier performed when it can be represented as a single task than when it is considered as two separate tasks. Divided attention is probably an important aspect of dual task interference, which may be relevant for the processing of inputs and transfer of motor programs to the execution channel for reaction time. However, it does not explain how interference is actually produced. Inhibition of contralateral motor tracts during an attention-demanding task is likely to play a role also. This could explain why reaction time is not only delayed during concurrent movements, but also during a mental task (Pashler 1994).

Effect of a SAS

A startling stimulus causes a significant shortening of the voluntary movement performed in SRT tasks when applied together with the IS or at a short interval afterwards (Valls-Sole et al. 1995; Valls-Solé et al. 1999; Siegmund et al. 2001; Carlsen et al. 2004; Kumru and Valls-Sole 2006). The movement to be performed in a SRT paradigm is thought to be prepared by subcortical structures activated directly by SAS (Valls-Solé et al. 1999; Carlsen et al. 2004). Speeding up of the SRT by SAS is likely to depend on the degree of subcortical motor preparation (Valls-Solé 2004). Recently, it has been demonstrated that the size of the startle reflex response changes in parallel with the percentage shortening of reaction time, an observation that further relates the StartReact effect with the excitability of subcortical motor structures activated by the SAS (Kumru and Valls-Sole 2006; Kumru et al. 2006; Carlsen et al. 2006). In the present study, we found that test trials with SAS were significantly delayed with respect to control trials with SAS. This suggests that the subjects were not able to fully engage their subcortical motor pathways in the reaction when performing contralateral oscillatory movements as when the contralateral hand was at rest. One likely explanation for the difference is that the subjects could not fully prepare their subcortical motor structures before IS detection. Lack of sufficient motor preparation is likely to be a manifestation of dual task interference. Therefore, our findings suggest that, in addition to many other physiological aspects underlying the dual task interference effect (Lien and Proctor 2002), limited preparation of subcortical motor structures contributes to the delay of SRT. This does not exclude the simultaneous contribution of other mechanisms, such as slowness of sensory processing because of divided attention and active inhibition linked to the issuing of motor commands, in the generation of the dual task interference effect.

An indirect consequence of our findings is that the StartReact effect may not entirely depend on the excitablity of the subcortical motor structures. Part of the effect may be due to the intersensory facilitation (Nickerson 1973; Carlsen et al. 2004; Kumru et al. 2006). Certainly, SAS delivered together with the IS is likely to induce intersensory facilitation of reaction time due to increased energy of the IS. However, the shortening observed with intersensory facilitation is no more than 50 ms (Nickerson 1973; Gielen et al. 1983). The shortening induced by SAS on SRT is usually larger than 50 ms, suggesting additional effects to those of intersensory facilitation. The electromyographic and kinematic characteristics of the movement performed with the StartReact phenomenon are not distorted with respect to those of the movement performed without interference of SAS (Valls-Solé et al. 1999). Therefore, the tracts activated by the SAS should be the ones used for execution of the motor commands. However, for this effect to take place, subjects have to have a high degree of preparation of their subcortical motor tracts (Kumru and Valls-Solé 2006; Carlsen et al. 2006). The amount of motor preparation in SRT can be very high since there is no need for sensory processing (Henderson and Dittrich 1998) and, consequently, the StartReact effect can lead to reaction times of values similar to those of the startle reaction. However, when performing unilateral oscillatory tremor-like movements, subjects may not be able to reach the same level of motor preparation as when they are at rest, which will lead to reduction of the StartReact effect. The degree of motor preparation of the subcortical motor tracts may control the extent of reaction time shortening induced by SAS, ranging from intersensory facilitation at one end, when full preparation is not possible, to a speed of execution similar to the startle reaction (StartReact effect) at the other end, when subjects have been able to reach full preparation.

In conclusion, our results show that performing oscillatory movements with one extremity interferes with the execution of ballistic movements with the contralateral one. In this condition, motor preparation of the subcortical motor tracts was insufficient to lead to the StartReact effect. This suggests that reduced motor preparation is an important mechanism to account for the delay in executing SRT when simultaneously performing contralateral movements. Our observations can be of interest for physiological studies of interlimb coordination and could contribute to improve our understanding of the mechanisms underlying the dual task interference phenomenon.

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