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Research Article

A Dual-Task Paradigm to Study the Interference Reduction in the Simon Task

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Abstract. Analyzing RT distributions in the Simon task reveals that congruency effects decrease for the longest RTs. Four experiments were carried out to examine whether this decrease of the congruency effect with response speed was under a top-down control or due to bottom-up mechanisms. We specifically manipulated the availability of attentional resources by requiring participants to perform a Simon task concurrently to different secondary tasks. RT distribution analysis (in particular delta functions) was performed under both single-task and dual-task conditions. Results show that the reduction of the interference effect with time could be affected when the Simon task was performed concurrently with a secondary task. Nonetheless, the type of the secondary task seems to be a critical factor. Therefore, the data suggest that the mechanisms responsible for the reduction of the interference effect with time are under some attentional control but the exact nature of these mechanisms remains to be explored.

Keywords: Simon task, interference control, attention, dual-task, RT distribution analysis

We are constantly dealing with different and complex stimuli from the environment. To behave successfully we need to distinguish and select relevant stimuli from interfering irrelevant ones which compete for control of action. Such irrelevant stimuli may automatically activate an erroneous response that we need to suppress. This ability has been largely described as response inhibition and is a key component of goal-directed behavior. It refers to the suppression of prepotent response tendencies when they are automatically activated but inappropriate. This type of inhibition is traditionally studied in paradigms known to activate concurrently competing response tendencies such as the Simon task (Simon, 1969).

In a standard version of the Simon task, participants have to choose between a left-and a right-hand key press according to the color of a visual stimulus presented either to the left or the right of a central fixation point. The performance, expressed both in terms of error rate and reaction time (RT), is better when the required response corresponds spatially to the stimulus location (congruent association) than when it does not correspond (incongruent association), even though this location is irrelevant. This effect is called "Simon effect" or "congruency effect" (Hedge & Marsh, 1975; Hommel, 2011; Simon, 1990).

A widely accepted interpretation of the Simon effect is that the stimulus location automatically triggers a response impulse in the ipsilateral hand by a fast route while the relevant stimulus color must be translated into the required response according to the task instructions by a slower controlled route (De Jong, Liang, & Lauber, 1994; Kornblum, 1994; Proctor, Lu, Wang, & Dutta, 1995). When the stimulus-response association is congruent, the impulse triggered by the irrelevant stimulus location activates the required response, which facilitates response processing. In contrast, when the stimulus-response association is incongruent, the impulse triggered by the irrelevant location activates the non-required response which competes with the required one. This competition is thought to be at the origin of a performance impairment (expressed as increased RTs and error rates).

Besides those standard measures, a detailed analysis of RT distributions revealed that congruency effect decreases as RTs lengthen (De Jong et al., 1994). A convenient way to visualize this effect is by using delta function, which plots the size of the congruency effect as a function of increasing RTs (for more details, see Ridderinkhof, Scheres, Oosterlaan, & Sergeant, 2005 and below). In the Simon task, delta functions turn negative-going as RT lengthen, showing a decrease in the interference. This decrease in congruency effect for the longest RTs implies that the condition inducing the shortest mean RT (congruent trials) is associated with the largest RT variance. This intriguing result violates the general finding that RT standard-deviation normally grows linearly with mean RT (Schwarz & Miller, 2012; Wagenmakers & Brown, 2007; Wagenmakers, Grasman, & Molenaar, 2005).

The nature of the processes leading to such a decrease remains a matter of debate. Some authors as Ridderinkhof (2002a) proposed that negative-going slopes could reflect an active mechanism for suppressing the automatic activation

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due to the irrelevant dimension of the stimulus. But some others proposed that the decrease of interference effects at the end of the RT distribution might simply result from a process of passive decay of the automatic response activation (Hommel, 1994). In the present study, we investigated whether mechanisms responsible for this negative-going slopes are under a top-down control or whether this decrease of Simon effect with response time reflects bottom-up processes. In this aim, we searched for boundary conditions in which this decrease in congruency effect for longest RTs did or did not occur. We reasoned that if top-down mechanisms are at the origin of this unusual negative-going delta functions, this decrease of congruency effect with time should, at minimum, be sensitive to attentional manipulation. Therefore, in the present study we manipulated the availability of attentional resources to investigate whether the decrease of congruency effect depends on attention.

Performing two tasks at once instead of separately leads to competition or division of attentional resources, provided that the two tasks share common processes. By consequence, dual-task protocols that require the concurrent performance of two independent tasks have often been used to investigate impact of limited attentional resources. Since Navon and Gopher (1979), many dual-task studies have demonstrated task performance impairments especially in terms of response speed, and/or accuracy (Hazeltine, Teague, & Ivry, 2002; Pashler, 1984; Schumacher et al., 2001) when participants have to deal with additional task requirements.

In the past, dual-task procedure in the Simon task has already been used but mainly to study whether the activation of the response that spatially corresponds to the location of the stimulus was endogenously or exogenously driven (Müsseler, Koch, & Wühr, 2005; Müsseler, Wühr, & Umiltá, 2006; Proctor & Lu, 1994) or to study the effect of dual-task on sequential effects (Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002). Here, we used it to more deeply investigate the nature of mechanisms responsible for the decrease of interference for slower RTs. In the present study, the same classic version of the Simon task was used in all experiments: Participants had to press a right or left response-key on the basis of the color of the stimulus presented either on the right or on the left of a central visual fixation point, and the availability of attentional resources was decreased by performing another completely unrelated task simultaneously with the Simon task. By comparing delta-function slope obtained in the Simon task performed either alone as a single task (ST) or under dual-task condition (DT), we investigated whether mechanisms responsible for congruency effect decrease was sensitive to attentional limitations. If it was the case, the negative going slope of the delta-functions should be affected in the DT condition, and more specifically should decrease or even increase into a more positive slope.

The predominant way to interpret dual-task performance is to consider that dual-task costs occur because tasks must compete for access to a central pool of limited resources that have to be shared between different tasks. However it is also feasible that central interference depends on the composition of particular tasks. This is the case in content-dependent theories (Navon & Miller, 1987; Pashler, 1990). A well-known class of content-dependent theories includes multiple-resources theory (Wickens, 1980, 1984) in which interference is maximized when two tasks require similar pools of resources. Wickens, Sandry, and Vidulich (1983) proposed that dual-task interference depends critically on the interaction between the type of central code (spatial vs. verbal), the type of input modality (auditory vs. visual), and the output modality (manual vs. speech). According to this multiple-resources theory, only tasks that compete for the same pool of mental resources should interfere with one another, tasks that do not require overlapping resources should not affect each other. Therefore, in the present study, we used two different secondary tasks. Initially we tried to maximize overlap between the Simon task and a secondary visuo-motor tracking task which requires visual stimuli, manual responses, and a spatial code, similarly to the Simon task. Afterwards to generalize our investigation, we used a duration-production task which shares less characteristics with the Simon task but is known to be extremely attention-demanding. Indeed, it has been shown in a large amount of experiments that temporal processing relies upon an internal clock which needs attention to function efficiently (for reviews, see Block, Hancock, & Zakay, 2010; Brown, 1997; Burle & Casini, 2001; Casini & Macar, 1997; Macar, Grondin, & Casini, 1994; Hicks, Miller, Gaes, & Bierman, 1977; Thomas & Weaver, 1975).

General Method

Participants

All participants had normal or corrected to normal vision, were paid for their participation and gave written, informed consent to the experimental procedure, following the Helsinki declaration (1964). The study was approved by the "Comité de Protection des Personnes Sud Méditerrannée 1" (N° 1041), in agreement with the French law.

Apparatus and Procedure

Participants were seated comfortably in a dimly lit sound-shielded room, facing a black panel, which was located 1 m away and delivered stimuli used in both tasks. Responses were given with devices specific to each experiment. All stimuli and responses were controlled by a home-made computer program. RTs were recorded at the nearest millisecond.

In all experiments participants performed three tasks (a secondary task, a Simon task, and a dual-task) in a counterbalanced order across participants. A training session for each task was performed by each participant to obtain more reliable performance.

In the Simon task participants were required to press a right or a left response button depending on the color (green or red) of a light emitting diode (LED) located either on the right or on the left of a central fixation point, as fast and as accurately as possible. The color-response mapping was balanced across subjects. For each color, there were two types of trials: congruent (CG) trials (response side ipsilateral to stimulus side) and incongruent (IG) trials (response side controlateral to the stimulus side).

Analysis of Results

In each of the three experiments we compared performance obtained in single task condition (ST) and in dual-task condition (DT) for each task.

For the Simon task, a first 2-way ANOVA with the following design, 2 congruency conditions (CG vs. IG) $\times$ 2 attentional conditions (ST vs. DT), was performed on RTs and accuracy rates. In addition to analyses of overall performance (accuracy and mean RT), distribution analyses were performed for error rates and for RTs. For chronometric analysis, the cumulative density functions (CDFs) of correct trials were estimated for each participant and averaged through the so-called "vincentizing" procedure (Ratcliff, 1979; Vincent, 1912): Single-trial RTs were rank ordered for each type of trials separately (CG trials and IG trials), and binned into quintiles of equal frequencies (same number of trials). The mean of each bin was computed and equivalent bins were averaged across participants. Delta-plots were constructed by plotting the difference between incongruent and congruent bins, as a function of the mean of incongruent and congruent bin values (for more information, see Burle, Possamaï, Vidal, Bonnet, & Hasbroucq, 2002; Ridderinkhof, 2002a). For distributional accuracy analysis, we computed the so-called "conditional accuracy functions" (CAFs): Correct and erroneous trials were mixed together and the resulting distributions were vincentized as described above. Five bins (quintiles) were used in the present set of experiments. For each bin, the proportion of correct trials was computed along with the mean RT of the bin. These couples of data were averaged per bin through participants. This provides the mean accuracy as a function of increasing RTs.

A 3-way ANOVA with the following design, 2 congruency conditions (CG vs. IG) $\times$ 2 attentional conditions (ST vs. DT) $\times$ 5 quintiles, was performed on RTs and on error rates. Indeed, although delta-functions are plotted for sake of simplicity and comparability, all statistical analyses were performed on the vincentized CDFs.

Since percentages cannot be submitted to ANOVA directly, as the means and variances of percentages tend to be closely related, error rates were arc-sine transformed before being analyzed (Winer, 1970).

Experiment 1

The purpose of the first experiment was to investigate whether mechanisms responsible for the decrease in congruency effect with response speed was sensitive to attentional limitations. In this aim we decreased attentional resources available for the Simon task by requiring participants to perform the Simon task simultaneously to a visuo-motor tracking task.

Our hypothesis was that 1/ the visuo-motor tracking task should capture attention yielding to performance impairments in the Simon RT task under DT condition, and 2/ if mechanisms responsible for the decrease of interference with time were sensitive to attention, the negative going slopes should be reduced under DT condition.

Method

Participants

Eighteen volunteers took part in the experiment (9 women and 9 men, mean age: 25 years, range: 20–30 years).

Apparatus

Participants were seated facing a black screen that displayed a white vertical irregular moving curve and a cursor (length: 30 mm, width: 5 mm) located in the middle of the screen and used to track the curve. Two LEDs horizontally aligned and spaced 2.5 cm apart were fixed to the screen on each side of the cursor also serving as a fixation point for the Simon task (Figures 1A and B). The two LEDs could be red or green. In the visuo-motor task, participants used a steering wheel (diameter: 15 cm) to maintain the cursor on the curve. Two response buttons were fixed to the

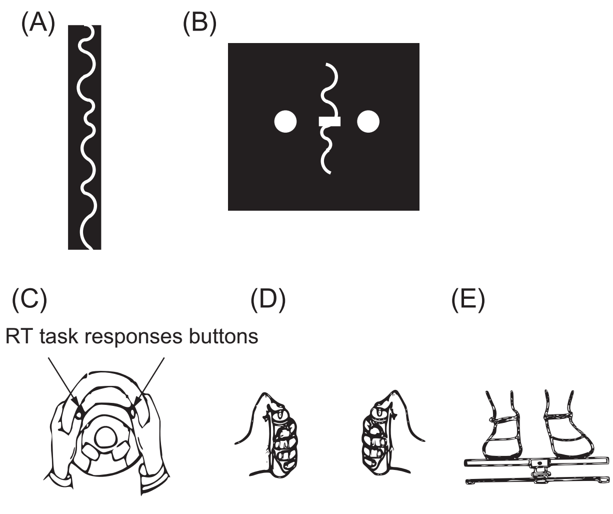

Figure 1. Experimental apparatus in Experiments 1–3. (A) An example of moving curve. (B) Stimuli panel. (C) Response device used for visuo-motor tracking and Simon tasks in Experiment 1. (D) Response buttons used for Simon task in Experiments 2 and 3. (E) Response device used for the visuo-motor tracking task with feet in Experiment 3.

steering wheel (at 10:00 and 2:00 o'clock) and were used to give responses in the Simon task (Figure 1C).

Procedure

Training Session

Participants performed one block of 12 trials for the visuo-motor task and one block of 48 trials for the Simon task and the dual-task. The procedure of the training session was the same as the experimental session, the details are given in the experimental session.

Visuo-Motor Tracking Task (Experimental Session)

An irregular moving curve was displayed on the screen. Participants had to track this curve with the cursor controlled by the steering wheel. Once participants had self-initiated the trial onset by pressing one of the two RT response buttons, the white cursor appeared in the middle of the screen and the participants had to keep the cursor on the curve that moved from right to left and vice-versa. Participants performed 2 blocks of twelve 25 s trials.

Simon Task (Experimental Session)

Participants had to briefly press one of the two response buttons as quickly as possible with the left or the right thumb according to the color of the LED. Participants initiated the trial onset by briefly pressing one of the RT response buttons. As soon as they pressed it, a brief tone of 600 Hz serving as a warning stimulus was delivered and a small horizontal line similar to the cursor used for the visuo-motor tracking task appeared on the screen serving as a fixation point. After a variable delay (ranging from 250 ms to 600 ms) following the warning signal, one of the two lateral LEDs lighted up either in green or red. Participants performed 2 blocks of 96 trials each. Within each block, there were 48 green and 48 red stimuli and for each color, there were 24 congruent trials and 24 incongruent trials.

Dual-Task (Experimental Session)

Participants were required to track the irregular moving curve and to perform the Simon task simultaneously. Once participants had self-initiated the trial onset by pressing one of the two RT response buttons, the white cursor appeared in the middle of the screen and participants had to keep the cursor on the curve that moved from right to left and vice-versa. During the 25 s of visuo-motor tracking, 8 trials of the Simon task were presented. They were all initiated by a sound, serving as warning signal. Participants performed 2 blocks of twelve 25 s trials. Congruent and incongruent trials were distributed as in the Simon task.

Results

Visuo-Motor Tracking Task

To evaluate performance of the visuo-motor tracking task, for each trial we measured two variables: The error rate, which was the number of times the cursor went off the curve, and the error time, which was the time the cursor was outside the curve. Paired *t*-tests were used to compare these variables in ST and DT conditions. There was no difference between attentional conditions for the error rate ($t_{17} = 1.42$, $p = .17$) and for the error time ($t_{17} = .87$, $p = .39$).

Simon RT Task

Mean RT and Accuracy

Figure 2A illustrates mean RT as a function of attentional conditions and for CG and IG trials. Participants were faster in ST (349 ms) than in DT (369 ms) conditions, $F(1, 17) = 6.67$, $p < .01$, and they also were faster in CG trials (345 ms) than in IG trials (373 ms), $F(1, 17) = 95.03$, $p < .001$. In addition, the congruency effect was larger in DT (33 ms) compared to ST (21 ms) as confirmed by the significant Attention × Congruency interaction, $F(1, 17) = 6.32$, $p < .05$. Figure 2B represents mean error rate as a function of attentional conditions and for CG and IG trials. Error rates were not different between attentional conditions, $F(1, 17) = 2.27$, $p = .14$, but were larger in IG trials (3.5%) than in CG trials (1.8%), $F(1, 17) = 8.28$, $p < .01$. There was no interaction between the two factors, $F(1, 17) = .30$, $p = .58$.

Distribution Analysis

Figure 2C displays delta-plots for RTs in ST and DT conditions. As confirmed by the significant second-order interaction between Attention, Congruency, and Quintiles, $F(4, 68) = 3.72$, $p < .01$, the evolution of the congruency effect size with the quintiles was different in ST and DT conditions. In ST, the Simon effect classically decreased with the longest RTs whereas the Simon effect remained stable across quintiles in DT. This is confirmed by the significant difference of the last slope values between ST and DT conditions, $F(1, 17) = 5.12$, $p < 0.05$.

Figure 2D illustrates CAFs for IG and CG trials in ST and DT conditions. Distributions of error rates were different for CG and IG trials (Congruency × Quintile: $F(4, 68) = 22.98$, $p < .0001$), but attention did not affect this interaction (Attention × Congruency × Quintile: $F(4, 68) = .59$, $p = .67$). One can note that the difference in accuracy between IG and CG mainly comes from the first quantiles.

Discussion

We investigated whether mechanisms responsible for the decrease of congruency effect with time were impaired

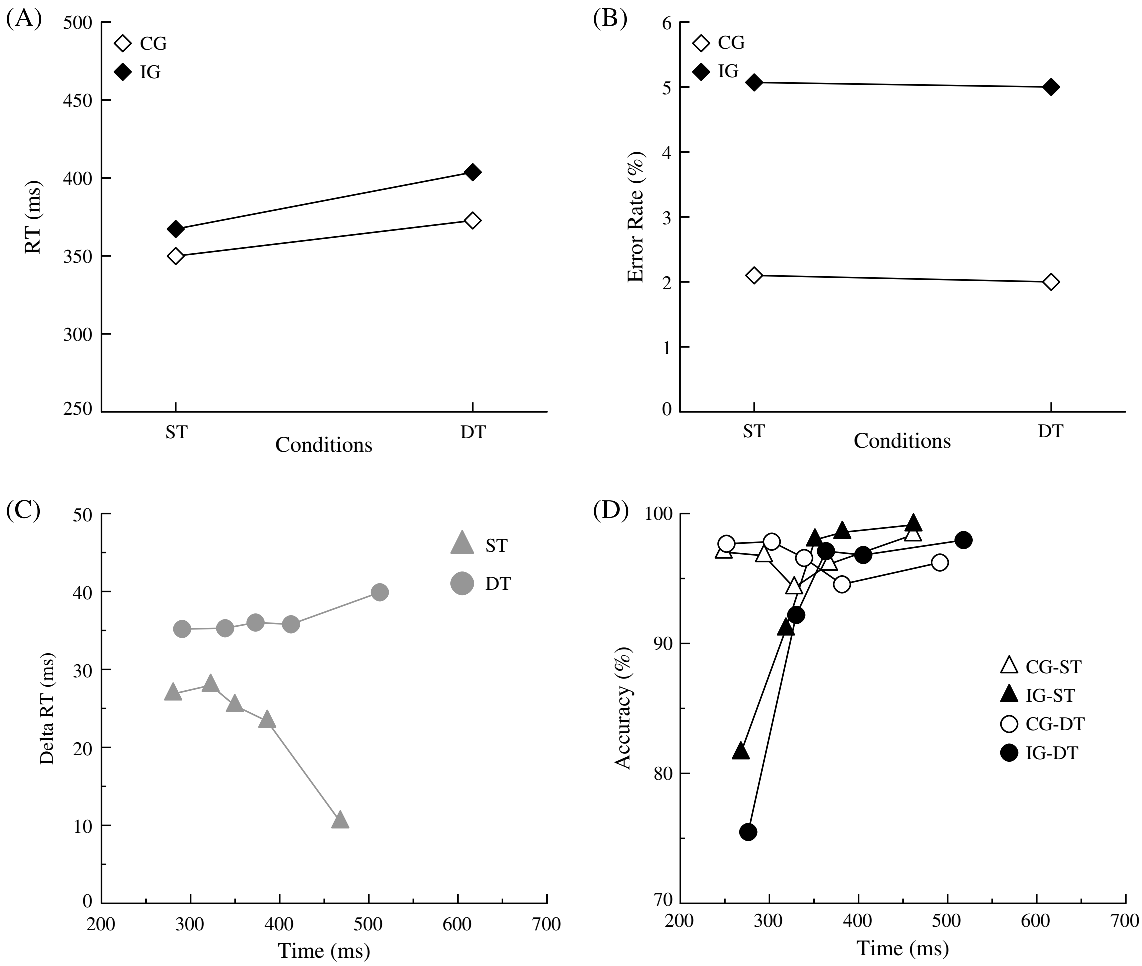

Figure 2. Experiment 1. (A) Mean reaction time for congruent (white diamond) and incongruent (black diamond) trials under single (ST) and dual-task (DT) conditions. (B) Mean error rate for congruent (white diamond) and incongruent (black diamond) trials under single (ST) and dual-task (DT) conditions. (C) Delta functions showing Simon effect size as a function of response speed (as expressed in reaction time (RT) quintile scores) under single task (gray triangle) and dual-task (gray circle) conditions. (D) Conditional accuracy functions for congruent (CG) and incongruent (IG) trials under single (ST) and dual-task (DT) conditions.

by restricted attentional conditions due to DT performance. First of all, we found significant performance decrements in the Simon task when performed under DT compared to ST: Responses were much slower in dual-task condition. This shows that performing the visuo-motor tracking task was efficient to produce an attentional cost for Simon task performance. Moreover the congruency effect was larger in DT compared to ST, which suggests that the control of interference was more difficult when subjects performed the visuo-motor tracking task simultaneously, even though the strength of the automatic capture by the irrelevant position stimulus was similar in ST and DT as shown by CAFs.

Even more interesting for the present purpose, if the distribution analysis of RTs revealed the classically observed decrease of the Simon effect with the longest RTs in ST, this was not the case in DT, as confirmed by the significant second-order interaction. In other words, the negative going slope did not occur when the Simon task was performed simultaneously with a visuo-motor tracking task. These results suggest that attentional load prevented the decrease of congruency effect with response speed indicating that mechanisms involved in the decrease of the Simon effect depend on attentional resources and therefore seem under top-down control.

Nonetheless, two points deserve further investigations to more strongly assess our conclusions. First, it can be noted that the Simon task was not strictly the same when performed under ST and DT conditions. Indeed, under ST the fixation point was a fixed cursor in the center of the screen whereas under DT, the fixation point moved on the line. Hence, in DT but not in ST, participants had a left-right dynamic reference in the middle of the screen which could have prevented a decay of the spatial response code. Therefore, it seems important to make sure that the ST/DT manipulation was not confounded with the difference of visual display. The second point is that the Simon task and the visuo-motor tracking task used the same effectors, namely the hands. It raised the question to know whether the decrease of the interference effects for longer RTs would be dependent on the effectors used or on more general motor resources. Two supplementary experiments addressing each one of these two questions have then been carried out.

Experiment 2

This experiment was aimed at testing whether the type of fixation point could modulate the decrease of interference with time. We compared delta-plots obtained in two Simon tasks performed as a single task but using different fixation points, either a static one or a dynamic one.

Method

Participants

Eighteen volunteers took part in the experiment (10 women and 8 men, mean age: 25.9 years, range: 18–30 years old).

Apparatus and Procedure

Participants performed the Simon task in the same conditions as in Experiment 1 except that the fixation point was either a static cursor as the one used in the Simon task of the previous experiment or an irregular moving curve (similar to the ones used in Experiment 1) located in the middle of the screen. To respond, participants used two response-buttons, one in each hand (Figure 1D). Participants performed two Simon tasks, one with each kind of fixation point, in a counterbalanced order.

Results and Discussion

A 3-way ANOVA with the following design, 2 congruency conditions (CG vs. IG) × 2 fixation points (static vs. dynamic) × 5 quintiles, was performed on RTs. For accuracy, only one 2-way ANOVA including 2 congruency conditions (CG vs. IG) × 2 fixation points (static vs. dynamic) was performed.

Mean RT and Accuracy

Analyses revealed no difference in mean RT, nor in accuracy rate between the two conditions (RT: $F(1, 17) = 0.09$, $p = .92$; accuracy: $F(1, 17) = 0.10$, $p = .74$). And for both indices, there were no significant Fixation Point × Congruency interactions suggesting that the congruency effect had similar size whatever the nature of the fixation point (RT: $F(1, 17) = 2.01$, $p = .17$; accuracy: $F(1, 17) = 0.001$, $p = .96$). Values of mean RT and error rates are summarized in Table 1.

Table 1. Mean RT and error rate obtained in Experiment 2

	Static fixation point		Dynamic fixation point	
	CG	IG	CG	IG
Mean RT (in ms)	358 ± 42	379 ± 41	355 ± 36	383 ± 43
Error rate	5%	7.5%	5%	8%

Distribution Analysis

Figure 3 displays delta-plots in the two conditions of fixation point. As confirmed by the absence of significant second-order interaction Congruency × Fixation Point × Quintiles, $F(4, 68) = 0.77$, $p = .54$, we can observe that the congruency effect decreased with quintiles with the two types of fixation point (Congruency × Quintiles interaction with the static fixation point: $F(4, 68) = 232.53$, $p < .0001$; Congruency × Quintiles interaction with the dynamic fixation point: $F(4, 68) = 28.5$, $p < .05$). In addition, a comparison of the last bin slopes between the two conditions revealed no significant difference, $F(1, 17) = 0.37$, $p = .54$.

These results suggest that the type of fixation point did not influence mechanisms responsible for the negative-going slope observed on delta-plots. Consequently, the decrease of the Simon effect for longer RTs was not influenced by the nature of the fixation point, which suggests that the absence of this decrease in the Experiment 1 was probably due to the manipulation of the attentional load.

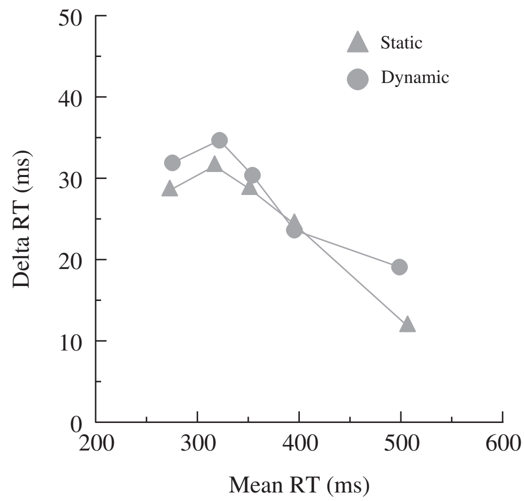

Figure 3. Experiment 2. Delta functions showing Simon effect size as a function of response speed (as expressed in reaction time (RT) quintile scores) with a static (gray triangle) and a dynamic (gray circle) fixation points.

Experiment 3

In this experiment, we investigated whether the decrease of the interference effects for longer RTs would be dependent on the effectors used or on more general motor resources. The Simon task was performed simultaneously to a visuo-motor tracking task performed with the feet instead of the hands.

Method

Participants

Twelve volunteers took part in the experiment (7 women, 5 men, mean age: 26 years, range: 20–30 years old).

Apparatus and Procedure

Stimuli were identical to those in Experiment 1. Concerning responses for the Simon RT task, participants used two response-buttons (Figure 1D), one in each hand, and for the visuo-motor tracking task they put their feet on a pedal (Figure 1E) and when they pushed with their right foot, the cursor moved to the right of the screen and when they pushed with their left foot, the cursor moved to the left of the screen. The procedure was identical to Experiment 1 except that participants tracked the moving curve with their feet and responded to the Simon RT task with two response buttons held in their hands.

Results and Discussion

Same analyses as in Experiment 1 were carried out.

Visuo-motor Tracking Task

There was no difference between ST and DT for the error rate ($t_{11} = 1.68$, $p = .12$), nor for the error time ($t_{11} = 1.71$, $p = .11$).

Simon RT Task

Mean RT and Accuracy

Figure 4A illustrates mean RT as a function of attentional conditions and for CG and IG trials. Participants were faster in ST (361 ms) than in DT (385 ms) conditions, $F(1, 11) = 14.84$, $p < .01$, and in CG trials (358 ms) compared to IG trials (388 ms), $F(1, 11) = 28.96$, $p < .001$. Moreover, the congruency effect was larger in DT (36 ms) compared to ST (23 ms) condition, as confirmed by the significant Attention × Congruency interaction, $F(1, 11) = 10.88$, $p < .01$. Figure 4B represents mean error rate as a function of attentional conditions for CG and IG trials. Error rates were not different between attentional conditions, $F(1, 11) = .35$, $p = 0.56$, but were larger in IG trials (5.03%) as compared to CG trials (1.9%), $F(1, 11) = 23.51$, $p < .001$. There was no interaction between the two factors, $F(1, 11) = .40$, $p = .53$.

Distribution Analysis

Figure 4C represents delta-plots as a function of quintiles, in ST and DT conditions. As confirmed by the significant second-order interaction Attention × Congruency × Quintiles, $F(4, 44) = 6.49$, $p < .001$, the Simon effect decreased with RTs in ST, but remained constant across quintiles in DT. This is confirmed by the significant difference between ST and DT conditions concerning the last slope of the delta function, $F(1, 11) = 8.71$, $p < 0.01$.

Figure 4D displays CAFs for IG and CG trials in ST and DT conditions. For both attentional conditions, accuracy rate was almost close to one in all quantiles for CG trials whereas in IG ones, accuracy rates were smaller for the first quintiles. The difference between CG and IG accuracy rates was large for the shortest RTs and then decreased when RTs lengthened in ST as in DT (Congruency × Quintile: $F(4, 44) = 16.52$, $p < .0001$; Attention × Congruency × Quintile: $F(4, 44) = 1.05$, $p = .39$).

The results of the present experiment replicate data obtained in Experiment 1: Performing a visuo-motor tracking task concurrently with a Simon task prevent negative-going slope to occur even when the two tasks involved different effectors. Therefore, using a secondary task drawing attentional resources from a general pool of resources devoted to motor responses seems sufficient to affect the decrease of the interference effect with time, which suggests that the mechanisms at the origin of this decrease interfere with mechanisms located at an upper level than execution ones.

To summarize, the combined data of these three experiments seem to suggest that mechanisms responsible for the decrease of the Simon effect with response speed are under top-down control. But as previously discussed, the visuo-motor tracking task overlaps largely with the Simon task, since it uses the same inputs, the same outputs and also relies upon a spatial code. Therefore, one last step before generalizing our conclusion, is to check whether the absence of the second-order interaction could also be found with a secondary task sharing less characteristics with the Simon task. The processing of temporal information is known to be very attention demanding and has been shown to interfere with a lot of different tasks (for review, see Brown, 1997) suggesting that it draws general attention resources. Moreover, we already found that simultaneously performing a choice reaction time task with a duration-production task yields a decrease of performance in both tasks (Burle & Casini, 2001). We therefore performed a final experiment using a duration production task as the secondary task.

Experiment 4

The purpose of this experiment was to investigate whether the mechanisms responsible for congruency effect decrease

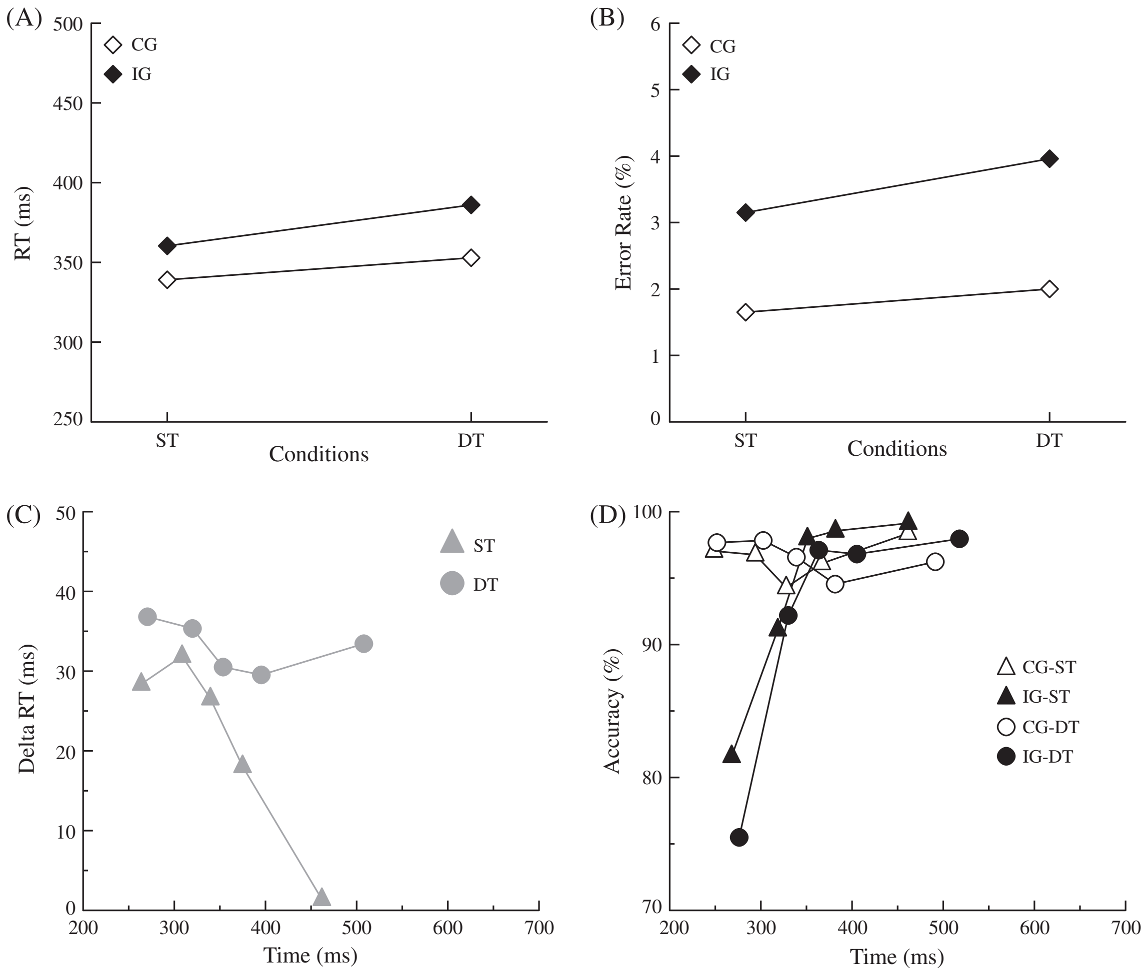

Figure 4. Experiment 3. (A) Mean reaction time for congruent (white diamond) and incongruent (black diamond) trials under single (ST) and dual-task (DT) conditions. (B) Mean error rate for congruent (white diamond) and incongruent (black diamond) trials under single (ST) and dual-task (DT) conditions. (C) Delta functions showing Simon effect size as a function of response speed (as expressed in reaction time (RT) quintile scores) under single task (gray triangle) and dual-task (gray circle) conditions. (D) Conditional accuracy functions for congruent (CG) and incongruent (IG) trials under single (ST) and dual-task (DT) conditions.

with response speed were sensitive to attentional limitations irrespective of the secondary task used.

Method

Participants

Eighteen participants participated in the experiment (10 women and 8 men, mean age: 25 years, range: 20–30 years old).

Apparatus

Participants were seated facing a black panel, which contained four light-emitting diodes (LEDs). Three LEDs were horizontally aligned and spaced 2.5 cm apart. The two lateral ones could be red or green and the central one was blue. The fourth LED (white) was 2.5 cm under the central blue one (see Figure 5A). In the Simon task participants used their right and left thumbs to press one of two response buttons fixed on a table in front of them (Figure 5B). In the duration-production task they used their knees to press a response device (Figure 5C) located between their legs (Vidal, Bonnet, & Macar, 1991).

Procedure

Duration-Production Task Training

The training session was made of two parts. The first part consisted of 20 trials. The illumination of the white LED indicating the beginning of the trial was followed by a tone (600 Hz) sounded during 1,100 ms. When the tone ended,

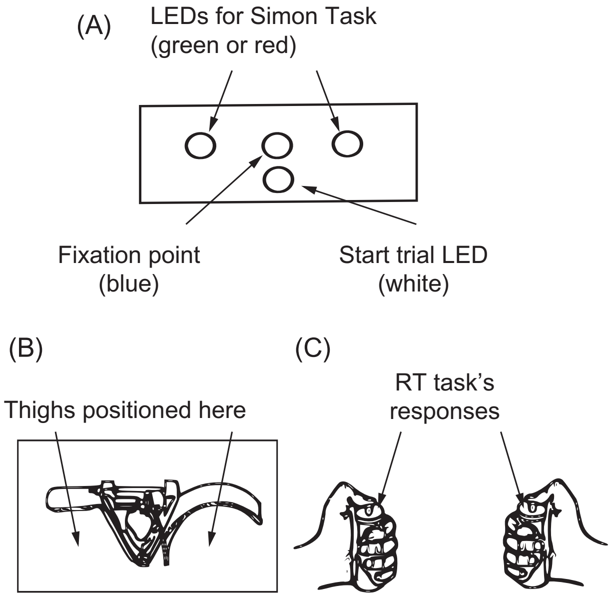

Figure 5. Experimental apparatus in Experiment 4. (A) Stimuli panel. (B) Device located between participant knees to produce duration intervals. (C) Response buttons for Simon task.

participants reproduced the duration of the tone by pressing the response device with their knees. The blue LED was lit during the whole time interval. When participants released the knee pressure, an auditory feedback was delivered. Five different feedbacks were used. If the produced interval was correct (less than 7.5% longer or shorter than the target), the word "correct" was delivered. If the produced interval was too long or too short (7.5%–22.5% longer or shorter than the target), either the words "*Trop long*" (too long) or "*trop court*" (too short) were delivered. If the duration was excessively long or short (more than 22.5% longer or shorter) the words "*beaucoup trop long*" (too much long) or "*beaucoup trop court*" (too much short) were delivered.

After the first 20 trials, the second part of the training was announced by the experimenter. In this part no additional model of target duration was delivered. Once the white LED lit up, participants had to produce the target duration (1,100 ms). As in the first part, an auditory feedback was delivered following each response. The participants continued until they produced 12 correct durations throughout 15 successive trials. On average, 32.2 trials (SD = 9.4) were necessary to reach the criterion.

Simon Task and Dual-Task Trainings

For the Simon task and the dual-task participants performed one training block of 48 trials. Since for both tasks the procedure of the training session was the same as the experimental session, the details are given in the experimental session.

Duration-Production Task (Experimental Session)

The participants' task was to maintain a key-press with their knees for 1,100 ms. Trial onset was initiated by participants once the white LED lighted. Participants had to maintain the knee-press as long as necessary to time the required duration. No feedback on performance was given. During the duration production period the central blue LED was lit, serving as a fixation point. Two seconds after the release of the key the white LED lighted-up again, indicating that the next trial could start. Participants performed one block of 96 trials.

Simon Task (Experimental Session)

Participants were required to press the right or the left response button depending on the color of the LED, as fast and as accurately as possible. Once the white LED lighted, participants initiated the trial onset by briefly pressing the knee-device. As soon as they pressed it, the central blue LED, serving as a fixation point and as a warning signal, lighted up. After a variable delay (ranging from 250 ms to 600 ms) following the warning signal, one of the two lateral LEDs lighted up either in green or red. Participants had to briefly press a response button as quickly as possible with the left or the right thumb according to the color of the LED. After a delay of 300 ms following the response, the white LED lighted up again and a new trial could be initiated.

Within each block, there were 48 green and 48 red stimuli and for each color, there were 24 CG trials and 24 IG trials. Participants performed 2 blocks of 96 trials each.

Dual-Task (Experimental Session)

In this condition, participants were required to produce the 1,100 ms target time duration and to perform the Simon task simultaneously. Each trial was similar to the duration-production task described above except that whilst participants were producing the required duration with their knees, after a variable delay (ranging from 250 ms to 600 ms) following the blue LED illumination corresponding to the onset of the produced duration, one of the two lateral LEDs appeared and participants had to respond appropriately as quickly as possible as outlined in the Simon task.

Results

Duration-Production Task

Mean produced duration was calculated for each subject in each condition. Mean produced duration reflects overall lengthening or shortening of produced time. Paired t-tests were used to compare mean produced durations in

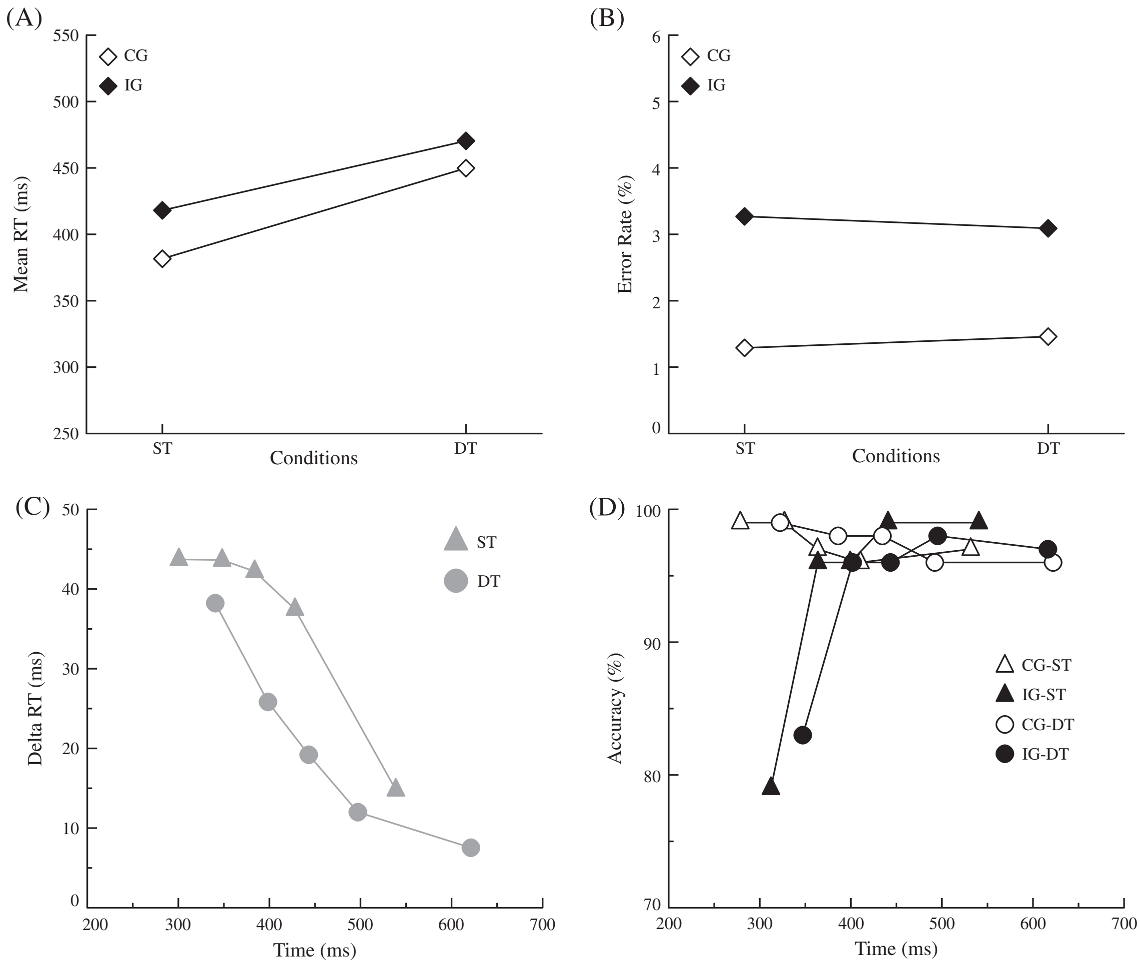

Figure 6. Experiment 4. (A) Mean reaction time for congruent (white diamond) and incongruent (black diamond) trials under single (ST) and dual-task (DT) conditions. (B) Mean error rate for congruent (white diamond) and incongruent (black diamond) trials under single (ST) and dual-task (DT) conditions. (C) Delta functions showing Simon effect size as a function of response speed (as expressed in reaction time (RT) quintile scores) under single task (gray triangle) and dual-task (gray circle) conditions. (D) Conditional accuracy functions for congruent (CG) and incongruent (IG) trials under single (ST) and dual-task (DT) conditions.

ST and DT conditions. Participants produced longer durations in DT (1,318 ms ± 159) as compared to ST (1,238 ms ± 163) ($t_{17} = 2.51$, $p < .05$). In DT condition there was no significant difference in produced durations between CG and IG trials ($t_{17} = 1.39$, $p = .18$).

Simon RT Task

Mean RT and Accuracy

Figure 6A shows mean RT as a function of attentional conditions for CG and IG trials. Participants were faster in ST (399 ms) than in DT condition (459 ms), $F(1, 17) = 35.14$, $p < .001$, and second, as classically reported, they were faster in CG trials (415 ms) than in IG trials (444 ms), $F(1, 17) = 37.55$, $p < .001$. Congruency effect was smaller in DT (20 ms) compared to ST condition (36 ms) as confirmed by a significant Attention × Congruency interaction, $F(1, 17) = 7.34$, $p < .01$. Figure 6B shows mean error rate as a function of attentional conditions for CG and IG trials. Error rates were not different between attentional conditions, $F(1, 17) = .11$, $p = .73$, but were larger in IG (3.18%) than in CG (1.37%) trials, $F(1, 17) = 12.85$, $p < .01$; there was no interaction between the two factors, $F(1, 17) = 0.31$, $p = .58$.

Distribution Analysis

Figure 6C displays delta-plots for RTs, representing the size of Simon effect as a function of quintiles in ST and DT conditions. Despite a marginally significant second-order interaction (Attention × Congruency × Quintile: $F(4, 68) = 2.37$, $p = .06$), the Simon effect decreased when RTs increased as confirmed by a significant

Congruency × Quintile interaction in each attentional condition (ST: $F(4, 68) = 6.26, p < .001$; DT: $F(4, 68) = 8.23, p < .001$). There was no significant difference between the last slope values obtained under ST and DT conditions, $F(1, 17) = 2.47, p = .14$.

Figure 6D displays CAFs for CG and IG trials, in ST and DT conditions. The distributions of error rates were different for CG and IG trials (Congruency × Quintile: $F(4, 68) = 17.7, p < .0001$, but this difference was not influenced by attentional conditions (Attention × Congruency × Quintile: $F(4, 68) = .61, p = .66$). In ST as in DT, accuracy was close to one for congruent trials whatever the quantile concerned, whereas accuracy was quite low for incongruent trials in the first quintiles.

Discussion

We investigated whether mechanisms responsible for the decrease of congruency effect with time were impaired when the Simon task was concurrently performed with a duration-production task known to be very attention-demanding. First of all, we found significant performance decrements in both tasks when performed under DT compared to ST. In the duration-production task, produced durations were longer under DT. This overproduction is one of the most systematically observed results when duration-production is performed under attentional distraction (Brown, 1997; Burle & Casini, 2001). In the Simon task, responses were much slower when the Simon task was performed as DT compared to when performed as ST. Even if there was no increased error rate in DT, the results show that DT manipulation was efficient to produce substantial cost on the attentional resources available for Simon task performance. Nonetheless, despite this attentional limitation, RT distribution analysis showed a decrease in the congruency effect for longer RTs in DT comparable to the one obtained in ST. Differently from what we observed in the previous experiments, this finding suggests that attentional manipulations, although sufficient in creating performance impairments, did not prevent the decrease of the interference effect with time.

Moreover, it is worth noting that the CAFs revealed no difference between ST and DT conditions, which suggests that the strength of initial response capture by the irrelevant stimulus location was not affected by DT manipulation. Smaller overall congruency effects observed in DT can therefore not be explained by a weaker automatic capture of the irrelevant location stimulus in DT. This reduction of congruency effect may perhaps be related to the lengthening of RTs in DT; indeed the response being delayed, the suppression of the automatically activated response could have more time to take place.

To conclude, it seems that in the present experiment, the reduction of Simon effect for longest RTs was exempt from the attentional manipulation, which suggests that the mechanisms responsible for this decrease would be dependent on specific attention resources.

General Discussion

Four experiments were carried out to investigate whether mechanisms involved in the decrease of congruency effect with time in the Simon task were under top-down control. For this purpose, we specifically manipulated the availability of attentional resources by performing a Simon task either as a ST or as a DT concurrently with different secondary tasks.

Our results showed that RTs lengthened in DT compared to ST in all tasks showing that the manipulation of the availability of attentional resources was successful. Moreover, when the Simon task was performed simultaneously with a visuo-motor tracking task, the delta functions revealed that the interference remained constant as RTs lengthened. This shows that it is possible to affect the reduction of the interference effect by reducing available attentional resources, which suggests that mechanisms responsible for the reduction of interference with time would be under attentional control. Therefore the present data support "active" mechanisms at the origin of interference reduction. In their original study, De Jong et al. (1994) proposed that negative-going slopes could reflect a mechanism for inhibiting irrelevant position information that strengthens over time. This idea was subsequently developed into the activation-suppression hypothesis (Ridderinkhof, 2002a, 2002b), which assumes that in the Simon task the automatic activation due to the irrelevant dimension of the stimulus can be actively suppressed. Since this suppression takes time to build up, the Simon effect disappears for longest RTs, as illustrated by the negative-going slopes of delta functions. This activation-suppression model and the associate negative-going slopes based on the idea of a top-down control have received strong support from several empirical data. For example, Burle, van den Wildenberg, and Ridderinkhof (2005) varied the temporal overlap between the onsets of the relevant and irrelevant stimulus dimensions and they observed negative slope values, that is, a reversal of the interference effect, if the irrelevant information was presented before the relevant information. The fact that long RTs were associated with a negative interference effect is consistent with more effective suppression. More recently, Hübner and Mishra (2013) used a similar procedure in two different conditions. Either the delay between a spatial cue and the target was randomly varied inside a block or each delay was presented in blocked trials. They observed that the overall Simon effect was larger when the delay was blocked but it remained positive, suggesting that the strength of the selective suppression can be adjusted strategically.

Nonetheless, the active nature of the underlying process has been disputed, mainly by Hommel (1994) who proposed that the decrease of interference effects at the end of the RT distribution might simply result from a process of passive decay of the automatic response activation. Although passive decay might potentially result in a reduction of interference effects with time, it is unlikely to account for reversals of the Simon effect observed in some

Table 2. Characteristics of the secondary tasks

	Visuo-motor tracking task	Duration production task
Negative-going slopes in DT	Yes	No
Stimulus modality	Visual	Visual
Response type	Limb movement	Limb movement
Spatial central code	Yes	No
Stimuli with spatial code	Yes	No
Existing S-R linkage	Yes	No

studies (Burle et al., 2005; Wylie et al., 2010). An interference effect below 0 means faster response selection on incongruent trials which would require an active process of suppression of the incorrect response activation during these trials. Our data also seem to speak against a pure spontaneous bottom-up process. Indeed, if it were purely spontaneous, and hence purely bottom-up, the reduction should not depend on attentional processes, and interference decrease should always be present even in DT condition. Of course, our data do not show that a spontaneous decay does not take place, but they rather suggest that a spontaneous decay alone cannot explain the reduction of the interference effect with increasing RT.

Nonetheless, if our results rather speak in favor of active mechanisms under top-down control, it should be noted that interference reduction was not observed in the Experiment 4 when participants performed the Simon task concurrently to the duration-production task. The decrease of interference effects was able to take place in this experiment where the effects of DT on RTs were the largest ones, demonstrating that the reason for the negative-going slopes to occur was not due to a default in the manipulation of attentional load. The most relevant hypothesis to explain differences observed depending on the secondary task used is that mechanisms responsible for the negative going slopes of the delta-plot would depend on specific attentional resources. According to the multiple resources theory first proposed by Wickens and colleagues (1983), tasks that compete for shared pools of mental resources should interfere with one another but should not affect other tasks that do not require overlapping resources. In this line, the visuo-motor task shares input modality, general motor resources and the same spatial central code with the Simon task (see Table 2), but the duration-production shared visual stimuli and motor responses with the Simon task, therefore resources coming from these two pools of resources would not be crucial for mechanisms involved in the control of interference, whereas resources needed to form the central spatial code would it be more. More recently, extending the idea of Wickens, some authors have also proposed that interference between tasks can occur even when there is no explicit overlap between the specific stimuli or responses for the two tasks, but because the stimuli activate existing linkages between input and output modalities (Hazeltine, Ruthruff, & Remington, 2006). According to this hypothesis, the selection of a motor response to a visual stimulus, as required by the Simon task, will engage a set of central operations that differ from those engaged by the production of durations, and the nature of the dual-task interference will differ accordingly. In this case, the relevant feature of the secondary tasks would be an existing linkage between visual stimuli and motor response, as it is the case for the Simon task. Lastly, the visuo-motor tracking task also involves stimuli with a spatial code, which was not the case for the duration-production task, therefore this characteristic of the stimuli could also be a key characteristic needed by the secondary task to affect the reduction of the Simon effect with time.

To conclude, the present work provided evidence that mechanisms responsible for the decrease of interference effect with time are affected by attentional manipulations, giving arguments in favor of a top-down control of mechanisms involved. But in a second step, it raised the question of the type of attentional resources needed by these mechanisms. In this line, finely varying the nature of the secondary task in order to determine which characteristics are crucial to affect the slope of the delta function seems an interesting way to get more information about the precise nature of mechanisms held responsible for the decrease of interference effects with time.

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