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Response selection involves executive control: Evidence from the selective interference paradigm

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In the present study, we investigated whether response selection involves executive control, using the selective interference paradigm within Baddeley's (1986) working memory framework. The interference from response selection was estimated by comparing the patterns of dual-task interference of simple and choice RT tasks with those of a number of established working memory tasks. In Experiment 1, we compared impairment of forward and backward verbal serial recall from the RT tasks and articulatory suppression. Experiment 2 measured the adverse effects of the RT tasks and matrix tapping on forward and backward visuospatial serial recall. Finally, in Experiment 3, we examined the impairment from the RT tasks with two measures of executive control—namely, letter and category fluency. Altogether, the three experiments demonstrated that response selection interferes with executive control and that the interference is not produced at the level of working memory's slave systems, which supports the assumption of executive involvement in response selection.

The notion of an *executive* system refers to a domain-free, limited-capacity attentional mechanism that is responsible for the control and coordination of cognitive processes during complex cognitive tasks. For many years, executive control has been one of the least understood parts of human cognition. At the outset of executive function research, ill-defined concepts, such as planning or problem-solving, were used as references of executive control (see Rabbitt, 1997, for a review). Over the years, these higher level concepts have been refined into a number of more basic executive functions, such as inhibition, switching, or updating (e.g., Miyake et al., 2000). It is obvious that the tasks used to measure these functions call on an array of processes and that some, but probably not all, of these processes involve control of attention, or executive control. Thus, underlying the traditionally proposed executive functions, more fundamental processes of executive control may be at work.

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In recent years, a number of studies in which various paradigms from cognitive psychology have been employed have suggested that executive control might be involved in response selection (Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002; Hegarty, Shah, & Miyake, 2000; Klauer & Stegmaier, 1997; Rowe, Toni, Josephs, Frackowiak, & Passingham, 2000; Smyth & Scholey, 1994) or in a response selection task (i.e., a choice reaction time [RT] task; Allain, Carbonnell, Burle, Hasbroucq, & Vidal, 2004). Nevertheless, the idea that response selection is executively controlled remains somewhat controversial. One reason for the controversy might be that the term *executive* has always been associated with higher order cognition, whereas response selection is, instead, believed to be a basic process. Another reason could be that the idea of an executively controlled response selection process is uninviting, since virtually every cognitive task involves response selection. In this view, almost every cognitive task requires executive control to some extent. As a consequence, even the use of simple secondary tasks, such as spatial tapping and articulatory suppression, might raise problems if it appears that, at least under particular conditions, these tasks require an executively controlled response selection process (Hegarty et al., 2000). We suggest that this skepticism is largely a result of the rather loose usage of the term *response selection*. To avoid any such ambiguity, in the context of the present study, *response selection* is understood as "a decisional stage about the identity of a required reaction"

(Schubert, 1999, p. 422). This definition imposes a restriction, in the sense that not every produced response is the result of a deliberate choice process.

Present Study

This study was set up in order to investigate whether executive control is involved in response selection. The experimental rationale was based on the selective interference paradigm, using Baddeley's (1986) working memory (WM) model as a theoretical framework. The original WM model proposes that the architecture of WM comprises two slave systems, one for short-term maintenance of phonological information (the phonological loop) and a similar one for visuospatial codes (the visuospatial sketchpad [VSSP]). These two storage systems are controlled and coordinated by a supervising agent, the central executive, which is assumed to be responsible for executive control.

In the present study, the interference due to response selection was estimated by comparing the patterns of dual-task interference from a simple and a choice RT task when simultaneously executed with a number of established WM tasks. According to several authors, the difference between both RT tasks lies in the fact that the choice RT task involves response selection, in the sense of a decisional stage about the identity of a required response, whereas the simple RT task does not (Donders, 1868/1969; Frith & Done, 1986; Schubert, 1999).

The hypothesis of the present investigation is that the requirement to select among responses calls on executive control but does not require verbal or visuospatial processing. Accordingly, in Experiment 1, forward and backward verbal serial recall tasks were used in order to determine whether the interference due to a choice RT task is larger when the primary task requires more executive control and whether this interference is produced at the level of the phonological loop. In Experiment 2, forward and backward visuospatial serial recall tasks were used for a similar test at the level of the VSSP. Finally, a traditional neuropsychological task—namely, verbal fluency—was used in Experiment 3 to determine whether a choice RT task caused additional interference with executive control.

EXPERIMENT 1

The first experiment was designed to investigate whether the interference due to a choice RT task is larger when the primary task requires more executive control and whether this interference is produced at the level of the phonological loop. To that end, we compared forward and backward serial recall of consonants under single-task conditions and under three dual-task conditions in which forward and backward serial recall was simultaneously executed with the simple RT task, with the choice RT task, and with articulatory suppression (i.e., a task that selectively interferes with verbal processing).

In forward verbal serial recall, participants are asked to reproduce the verbal material in the same order of presentation, whereas in backward recall, the verbal material is recalled in the reverse order of presentation. Performance for backward recall is usually observed to be worse, as compared with forward recall, although different measures of performance and manipulations of the nature of the verbal material have produced some exceptions (e.g., Engle, Tuholski, Laughlin, & Conway, 1999; Farrand & Jones, 1996). By cuing the required direction either pre- or post-presentation of the items, early studies (Hinrichs, 1968; Nilsson, Wright, & Murdock, 1979) have demonstrated that participants reverse verbal material at encoding, and not at retrieval, provided that the direction of recall is known in advance. With respect to the nature of the cognitive processes involved in forward and backward verbal serial recall, there is nowadays a predominant view that Rosen and Engle (1997) called the *complexity* view, which explains the differences between both directions of verbal recall in terms of processing complexity or executive demands. It states that both forward recall and backward recall of verbal items involve a similar degree of phonological processing (Rosen & Engle, 1997) and that, besides the executive demands associated with verbal serial recall in general (e.g., Engle et al., 1999), backward recall requires a directional transformation that taxes additional executive resources, as compared with forward recall (Ashman & Das, 1980; Case & Globerson, 1974; Jensen & Figueroa, 1975; Schofield & Ashman, 1986). Over the years, several studies have supported the view that the reversing operation involved in backward verbal serial recall relies on executive control (Elliot, Smith, & McCulloch, 1997; Farrand & Jones, 1996; Gathercole, 1999; Gathercole & Pickering, 2000; Groeger, Field, & Hammond, 1999; Lezak, 1995; Smyth & Scholey, 1992; Vandierendonck, De Vooght, & Van der Goten, 1998a, 1998b).

The evidence for a comparable verbal involvement and a differential executive involvement in forward and backward verbal serial recall tasks offers a rationale for implementing the latter tasks in a selective interference paradigm, in order to dissociate verbal from executive involvement in an interference task. Given that participants perform the directional transformation at encoding when the direction of recall is precued, it can be anticipated that also in a blocked design, where the direction of recall is manipulated in two conditions, the reversing will be performed during the encoding of the verbal material. In addition, given that the reversing operation at encoding is executively demanding, it can also be expected that an executive secondary task concurrently performed during the encoding phase will differentially affect forward and backward verbal serial recall (as in Vandierendonck et al., 1998a, 1998b). Conversely, given that the verbal demands are comparable for both directions of recall (Rosen & Engle, 1997), a verbal secondary task can be anticipated to similarly affect forward and backward verbal serial recall.

On the basis of previous considerations, the following predictions were formulated for the present experiment. First, since the choice RT task involves response selection, whereas the simple RT task does not, we expected that the choice RT task would interfere more with forward and backward verbal serial recall than the simple RT task would. Second, if response selection is executively controlled and not produced at the level of the verbal WM slave system, we predicted that the choice RT task would impair backward verbal serial recall more adversely than forward verbal serial recall, whereas articulatory suppression would affect both directions of recall similarly. Before formulating the prediction associated with the simple RT task, we should point out that in all the experiments reported in this study, the duration of the interstimulus intervals (ISIs) of the simple and choice RT tasks was pseudorandomized, for the following two reasons. First, the inclusion of random ISIs induces executive demands in a simple RT task (Vandierendonck et al., 1998b). Such an executive control task is important for investigating whether a response selection process creates an additional executive load. Second, pseudorandom variable intervals reduce the probability that in a simple RT task, participants would respond on the basis of anticipation, rather than responding to the stimulus. Accordingly, we predicted that the simple RT task would also interfere more with backward than with forward verbal serial recall.

Method

Participants and Design. Forty-four 1st-year students enrolled at the Faculty of Psychology and Educational Sciences of Ghent University (Belgium) participated as a course requirement and for credit. They were randomly assigned to one of two reproduction instruction conditions (between subjects: 21 participants in the forward and 23 in the backward recall conditions), in which verbal serial recall was performed under a single-task condition and in concurrent execution with articulatory suppression, a choice RT task, and a simple RT task. These within-subjects conditions, which also included single-task simple RT and choice RT conditions, were counterbalanced according to a randomized Latin square.

Materials and Procedure. The consonants were chosen from 13 groups with low intergroup confusability according to their Dutch pronunciation. The groups were (B, D, P, T), (C), (F, S), (G), (H, K), (J), (L), (M, N), (Q), (R), (V, W), (X), and (Z). A string of consonants was composed by selecting one letter at random from each group, in order to minimize the phonological similarity between the letters. In the RT tasks, two different and easily discriminable tones with a frequency of 262 Hz (C1 note) and 524 Hz (C1 plus one octave) were used. Each tone lasted 200 msec. For both RT tasks, the interval between two consecutive bleeps was either 900 or 1,500 msec, randomly chosen with the constraint that no more than three consecutive intervals were of equal duration.

The participants were seated at an 80486 PC with a 15-in. color monitor. The instructions were presented on the computer screen, and the experiment started with a practice session that consisted of 2 single trials. A trial started with the presentation of a fixation cross (+) in the center of the screen and a sound. After 500 msec, the cross disappeared, and after a 2,000 msec blank screen, the first consonant was displayed for 1,500 msec, followed by a 500-msec blank screen before the next consonant appeared. The sequence ended with a sound and three exclamation marks (!!!), which were meant to trigger the reproduction. The participants were instructed to reproduce as many consonants as possible in the same or the reverse order of presentation, according to their instruction condition. Oral recall was registered by the experimenter. At the end of reproduction, the experimenter started the next trial. After the 2-trial practice, a verbal span task followed, which was also meant as practice and was not included in the counterbalancing scheme. The verbal span task started with a sequence of three consonants and ended with a sequence of eight consonants. Three trials were presented per sequence; each participant performed 18 trials (6 sequences × 3 trials), regardless of his or her individual performance.

After the practice sessions, the participants started with the six conditions that were included in the counterbalancing scheme. In the control condition, the participants performed the verbal span task alone. In the dual-task conditions, the participants had to perform a secondary task (simple RT task, choice RT task, or articulatory suppression) during the presentation phase of the memory task, but not during retrieval. The secondary tasks started 5,000 msec before the primary task began, and both the primary and the secondary tasks ended with the final sound that triggered primary task recall. For the simple RT task, the participants were required to hit the "0" key on the numeric pad with the index finger of the right hand as quickly as possible after they heard a tone. So as not to delay RT with movement time, the participants were instructed to rest the index finger of the right hand on the "0" key. During the choice RT task, the participants were required to hit the "1" key or the "4" key on the numeric pad as quickly as possible after they heard a low- or a high-frequency bleep, respectively. The participants were instructed to rest the index finger of the right hand on the "1" key and the middle finger on the "4" key, to avoid target-seeking movements between both keys. In the articulatory suppression condition, the participants were required to continuously repeat aloud the word *de* (Dutch for *the*). They were instructed that the pace should be not less than two and not more than three repetitions per second, and they practiced in such a way. The experimenter continuously verified that this pace was maintained throughout the experiment. The remaining two conditions that were included in the counterbalancing scheme were a single-task simple RT condition and a single-task choice RT task condition (each for 12 periods of 20 sec).

Results

The performance on the RT tasks will be analyzed and discussed after all three experiments have been presented. As the dependent variable for the verbal memory task, we used a transformation of Kendall's rank correlation coefficient tau, which reflects the proportion of stimuli recalled in correct relative order. This measure, τ', is obtained as follows:

$$\tau' = \frac{\sin^{-1}(\tau) + \pi/2}{\pi} \times \frac{n_r}{n},$$

where τ is the Kendall rank correlation between the presented and the recalled order of items, n is the number of presented items, and n_r is the number of recalled items. This formula yields an index between 0 and 1. Higher values denote that many items were recalled in correct order. Low values are obtained when the order is strongly violated or when only a few items are recalled. Commission errors are not taken into account. The proportions of consonants recalled in correct relative order were expressed as a function of a 2 (reproduction instruction: forward or backward) × 4 (condition: control, articulatory suppression, choice RT, or simple RT) mixed design.

The data obtained from the three experiments reported in this article were analyzed by means of a repeated measures analysis based on the multivariate general linear model. The main effects of reproduction instruction [$F(1,42) = 4.14$, $p < .05$] and condition [$F(3,40) = 121.31$, $p < .001$] were significant. The reproduction instruction × condition interaction [$F(3,40) = 3.24$, $p < .05$] was also significant. This interaction is displayed in Figure 1.

The predictions were tested by means of planned comparisons. These revealed that, under a single-task control condition, performance for forward and backward serial recall of consonants was comparable [$F(1,42) = 2.36$, $p > .10$]. Performance under articulatory suppression did not differ as a function of the reproduction instruction ($F < 1$): Articulatory suppression affected both forward [$F(1,42) = 188.26$, $p < .001$] and backward [$F(1,42) = 125.51$, $p < .001$] recall in a similar way. Recall was also impaired by the concurrent choice RT task, and this was larger for backward than for forward recall [$F(1,42) = 5.07$, $p < .05$]. The dual-task impairment due to the simple RT task was also larger for backward than for forward recall [$F(1,42) = 6.70$, $p < .05$], replicating a finding reported by Vandierendonck et al. (1998b). The interaction of reproduction instruction with the planned contrast between articulatory suppression and the choice RT task was significant [$F(1,42) = 6.44$, $p < .05$]. The interaction of reproduction instruction with the contrast between the choice and the simple RT tasks was not significant ($F < 1$).

Discussion

In line with the earlier findings described in the introduction to this experiment, we observed that the simple RT task interfered more with backward than with forward verbal serial recall, whereas articulatory suppression affected both directions of recall similarly. With respect to the choice RT task, we observed that in both recall conditions, the choice RT task affected primary task performance more than the simple RT task did. In accordance with the predictions, the findings also showed that the adverse effects of the choice RT tasks were more pronounced when the primary task required backward recall, as compared with forward recall. Furthermore, with respect to the patterns of interference with forward and backward verbal serial recall, we observed a parallelism between the choice RT task, and the simple RT task, on the one hand, and a dissociation between articulatory suppression and the choice RT task, on the other hand. The parallelism suggests that the choice RT task gives evidence of an executive pattern of interference, and the dissociation indicates that the interference due to the choice RT task is not verbally mediated. Hence, we conclude that the choice RT task interferes more when the primary task requires more executive control and that the interference is not produced at the level of verbal WM.

As was described in the introduction to this experiment, backward verbal serial recall is generally found to be poorer than forward verbal serial recall (but see Engle et al., 1999; Farrand & Jones, 1996). In the present study, we observed a similar level of performance for both di-

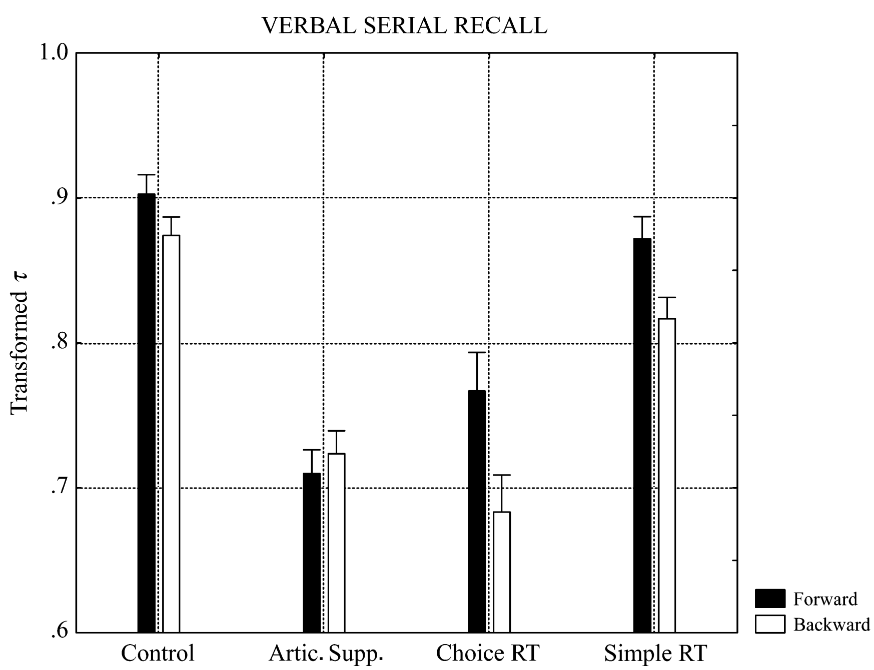

Figure 1. The proportion of consonants recalled in correct relative order (transformed τ) as a function of the 2 (reproduction instruction: forward or backward) × 4 (condition: control, articulatory suppression, choice RT, or simple RT) mixed design (Experiment 1). Bars denote standard errors.

rections of recall ($p = .13$). However, in the forward and backward verbal serial recall practice phase, which was always performed prior to the counterbalanced conditions (see the Materials and Procedure sub-section), we did observe a difference in performance in favor of the forward condition ($p = .02$). This suggests that the difference between forward and backward recall might have disappeared through the practice effects associated with the completion of five (one practice and four counterbalanced) verbal serial recall conditions in total. Interestingly, the additional executive demands associated with backward recall were not altered by practice. This shows that also when forward and backward recall yield similar levels of performance, the processing differences between both tasks remain measurable.

So far, the findings in Experiment 1 indicate that the interference effects of a task involving response selection are amplified when the executive load of the primary task is larger. Moreover, the interference does not seem to be produced at the level of the phonological slave system.

EXPERIMENT 2

The purpose of Experiment 2 was to further support the position that the choice RT task gives evidence of an executive pattern of interference and to examine the possibility that the interference from the choice RT task occurs at the level of the visuospatial WM slave system. Accordingly, a short-term memory experiment was designed in which a simple RT task, a choice RT task, and matrix tapping (i.e., a task that selectively interferes with visuospatial processing) were concurrently executed with a forward and a backward variant of the Corsi blocks task.

The Corsi blocks task requires participants to point to a series of blocks in the same (forward) or reversed (backward) order as that presented by the experimenter. It is a popular measure of visuospatial serial recall, which is considered to be the visuospatial counterpart of the verbal memory span task (for a review of the main findings, see Berch, Krikorian, & Huha, 1998). Despite the fact that both verbal and spatial serial recall were initially assumed to be equivalent measures of short-term memory, albeit in different modalities, there is a considerable amount of neuropsychological and experimental evidence that verbal and spatial serial recall are not similar in all respects (see Smyth & Scholey, 1992, for an extensive review).

Regarding the nature of the WM processes involved in the forward version of the Corsi blocks task, it has been demonstrated that visuospatial and, to a lesser extent, also executive resources are deployed (Vandierendonck, Kemps, Fastame, & Szmalec, 2004; Vecchi & Richardson, 2001). Contrary to what holds for verbal span, it is a replicated finding that performance for spatial serial recall is not impaired by producing the items in reversed order (Isaacs & Vargha-Khadem, 1989; Vandierendonck et al., 2004; Wilde & Strauss, 2002). Smyth and Scholey (1992) attributed this to the fact that "in the spatial domain, it is possible for memory items to be maintained as a visouspatial pattern with no involvement of serial order" (p. 161). Hence, Smyth and Scholey (1992) suggested that whereas executive resources are required to reverse the order of presentation of verbal items, additional resources are not required to reverse the order of presentation of the spatial Corsi block items. This position is supported by the finding that an executive secondary task affects forward and backward recall of Corsi block sequences to a similar extent (Vandierendonck et al., 2004).

Another particularity of the Corsi blocks task is that the visuospatial demands seem to decrease in the backward version of the task. The latter position is supported by the observation that matrix tapping is more detrimental on forward than on backward recall (Vandierendonck et al., 2004) and by the neuropsychological finding that visuospatially impaired patients, as compared with a group of matched controls, give evidence of a similar level of performance for the backward Corsi blocks task but lower performance for the forward version of the task (Mammarella, Cornoldi, & Donadello, 2003). Recently, Vandierendonck and Szmalec (2004) directly addressed the issue of decreased visuospatial resources in the backward Corsi blocks task. They suggested that performance on the backward memorization of block sequences benefits from a recency effect, in the sense that participants can recall the last three to four blocks without rehearsing them. This might explain why matrix tapping, a task that is known to interfere with the visuospatial rehearsal process (e.g., Logie, 1995), interferes less with the backward Corsi blocks task.

The evidence for a comparable executive involvement and a differential visuospatial involvement in forward and backward visuospatial serial recall tasks suggests that it should be possible to dissociate visuospatial from executive involvement in an interference task concurrently executed with the forward and the backward Corsi blocks tasks. Accordingly, Experiment 2 aimed to dissociate the executive from the visuospatial processing involved in a choice RT task by means of comparing the interference due to a choice RT task with the forward and backward Corsi blocks task with the interference due to an executive control task and matrix tapping.

On the basis of previous considerations, the following predictions were formulated. First, knowing that the Corsi blocks task involves executive control (Vandierendonck et al., 2004; Vecchi & Richardson, 2001), we expected that the choice RT task would interfere more with the Corsi blocks task than the simple RT task would. Second, according to Vandierendonck et al. (2004) and the evidence discussed in the previous paragraphs, we anticipated that the executive control task (simple RT task) would similarly affect the forward and backward variants of the Corsi blocks task similarly, whereas matrix tapping would interfere more with the forward variant. Finally, if response selection is executively controlled and is not produced at the level of the visuospatial WM slave system, we would expect that the choice RT task, like the executive control task, would affect the forward and the backward Corsi blocks tasks similarly, and that the choice RT task would dissociate from matrix tapping in terms of interference with forward and backward visuospatial serial recall.

Method

Participants and Design. Fifty-three 1st-year students enrolled at the Faculty of Psychology and Educational Sciences of Ghent University (Belgium) participated as a course requirement and for credit. None of them had taken part in Experiment 1. They were randomly assigned to one of two reproduction instruction conditions (between subjects: 28 participants in the forward and 25 in the backward reproduction instruction conditions), in which the Corsi blocks tapping task was performed in a single-task condition and in concurrent execution with matrix tapping, a choice RT task, and a simple RT task. These within-subjects conditions, which also included single-task matrix tapping, choice RT, and simple RT conditions, were counterbalanced according to a randomized Latin square.

Materials and Procedure. A computerized version of the Corsi blocks task was presented on a 15-in. touch screen. The nine blocks were 30 × 30 mm white squares, positioned on a blue background according to Corsi's (1972) original configuration. The presentation of a block sequence was monitored by the computer: Each block in turn was highlighted by changing its color from white to black for 1 sec, with an interblock interval of 0.5 sec.

The start of presentation was announced by a 400-msec 1000-Hz sound. The presentation ended with a 400-msec 100-Hz sound, which announced the reproduction phase. The participants were instructed to reproduce the highlighted blocks by touching the squares on the screen in the same or the reverse order of presentation, depending on the condition they were assigned to. When a square was touched by the participant, it turned black for 200 msec, in order to provide feedback on the touching operation. At the end of recall, the participant was required to hit the escape key, and after a 2-sec intertrial interval, the next trial started. A condition started with a sequence of three and ended with a sequence of eight blocks. Three trials were presented at each sequence length, so each condition consisted of 18 trials.

Instructions were presented on the computer screen. The experiment started with two practice trials and an entire single-task Corsi practice block, followed by the seven counterbalanced conditions. In the control condition, the participants performed the Corsi block-tapping task alone. In the dual-task conditions, the secondary tasks (matrix tapping, the choice RT task, and the simple RT task) were executed during the presentation of the Corsi block sequences, but not during retrieval. Matrix tapping required the participants to hit the four corners of the numeric keypad in counterclockwise order at a pace of two to three keys per second. This operation was registered in terms of accuracy and latency. The other secondary tasks were the same as those in Experiment 1. Performance on the three secondary tasks was also registered in a single-task situation (each task for 12 periods of 20 sec).

Results

With the same measure as that in Experiment 1 (τ'), the proportion of consonants recalled in correct relative order was expressed as a function of a 2 (reproduction instruction: forward or backward) × 4 (condition: control, matrix tapping, choice RT, or simple RT) mixed design.

The main effect of reproduction instruction was not significant ($F < 1$), whereas the main effect of condition was [$F(3,49) = 61.15$, $p < .001$]. The reproduction instruction × condition interaction [$F(3,49) = 6.68$, $p < .001$] was also significant. Figure 2 displays the interaction.

Planned comparisons showed that, in the single-task control condition, performance was comparable for both forward and backward serial recall of Corsi blocks ($F < 1$). Matrix tapping affected both forward [$F(1,51) = 96.73$, $p < .001$] and backward [$F(1,51) = 30.42$, $p < .001$] recall of block sequences, but the interference was significantly stronger for forward than for backward recall [$F(1,51) = 7.54$, $p < .01$]. The choice RT task interfered with forward [$F(1,51) = 54.97$, $p < .001$] and backward [$F(1,51) = 74.25$, $p < .001$] recall of Corsi block sequences. The degree of interference was comparable for both reproduction instruction conditions [$F(1,51) = 1.22$, $p > .10$]. The simple RT task did not affect forward recall [$F(1,51) = 2.46$, $p > .10$], whereas it did impair backward recall [$F(1,51) = 19.40$, $p < .001$]. However, the difference in simple RT task interference between both directions of recall failed to reach statistical significance [$F(1,51) = 3.93$, $p > .05$]. Furthermore, the interaction of reproduction instruction with the contrast between matrix tapping and the choice RT task was significant [$F(1,51) = 12.08$, $p < .01$], whereas the interaction of reproduction instruction with the contrast between the choice and the simple RT tasks was not ($F < 1$).

Discussion

Experiment 2 replicated the findings reported by Vandierendonck et al. (2004) and further demonstrated that, in terms of interference with the forward and backward variants of the Corsi blocks task, the response selection task dissociated from a visuospatial task but gave evidence of a pattern of interference similar to that of the executive control task. Accordingly, in line with the findings in Experiment 1 for the verbal domain, we can conclude that the choice RT task does not interfere at the level of the VSSP but probably does at the level of the central executive.

EXPERIMENT 3

So far, we have demonstrated that response selection contributes to a dual-task impairment that is not situated at the level of the slave systems. If response selection is not produced at the level of verbal or visuospatial processing, what is the basis of the observed effects? We have suggested that the interference is mediated by executive control, on the basis of the observation that the impairment of the choice RT task on verbal and visuospatial serial recall is comparable to a pattern of interference observed with another executive secondary task. Nevertheless, more direct evidence is needed to support

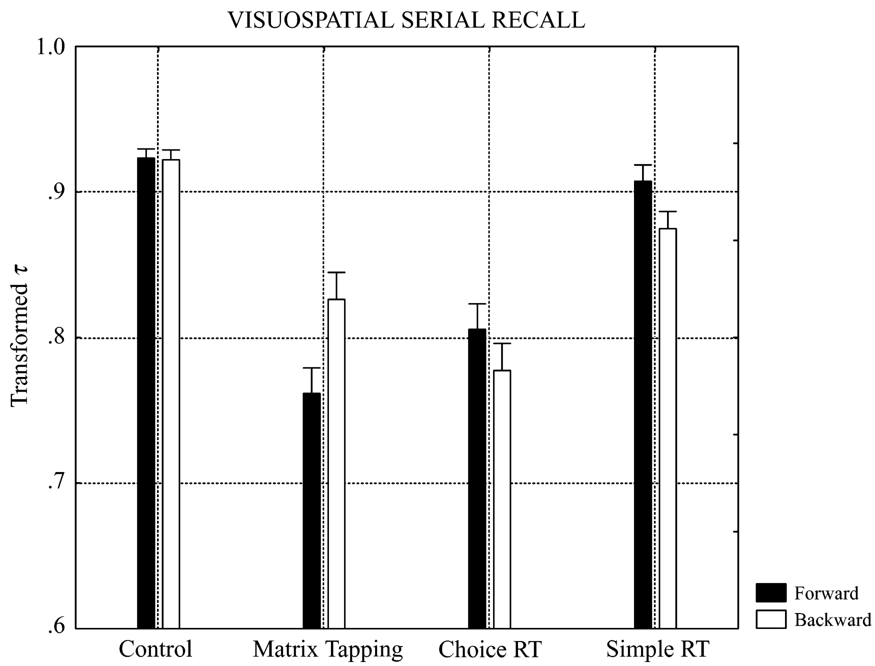

Figure 2. The proportion of blocks recalled in correct relative order (transformed τ) as a function of the 2 (reproduction instruction: forward or backward) × 4 (condition: control, matrix tapping, choice RT, or simple RT) mixed design (Experiment 2). Bars denote standard errors.

the latter position. However, this additional evidence is more likely to be obtained with other tasks than verbal or visuospatial serial recall tasks. The reason is that the extent to which those serial recall tasks involve executive control is rather limited (see Engle et al., 1999). Thus, despite the fact that those verbal and visuospatial span tasks are useful to dissociate executive from domain-specific processing, which was the main purpose of Experiments 1 and 2, a more demanding measure of executive control is needed to evidence the specifically executive demands of response selection more directly. Therefore, in Experiment 3, a well-established neuropsychological measure with high executive demands was used—namely, verbal fluency (e.g., Phillips, 1997; Rende, Ramsberger, & Miyake, 2002).

Verbal fluency usually requires a person to generate as many words as possible with a specified initial letter (letter fluency) or from a specified category (category fluency). Although verbal fluency was initially considered to be a relatively pure measure of frontal or executive functioning (e.g., Denckla, 1994), Rende et al. (2002) demonstrated that verbal and visuospatial processes also contribute to letter and category fluency, albeit in a different way. More precisely, the phonological loop seems to contribute to letter fluency, whereas the VSSP plays a similar role in category fluency. With respect to the executive contribution to verbal fluency, Rende et al.'s findings showed that the executive function of *mental set shifting* is equally involved in letter and category fluency tasks.

Taking into account these findings, a number of predictions were formulated for Experiment 3. First, if response selection involves executive control, a concurrent choice reaction task should have a more disruptive effect on a task that requires many executive resources (i.e., verbal fluency) than does concurrent simple reaction. The second prediction refers to the processing differences between letter and category fluency, as reported by Rende et al. (2002). If response selection is not mediated by verbal or spatial processing, the choice RT task is predicted not to differentially affect letter and category fluency. That is why the choice RT task is, instead, expected to cause a more general impact on verbal fluency, analogous to the arithmetic switching task that was used to operationalize the *task set shifting* executive function in the study of Rende et al.

Method

Participants and Design. Twenty-four 1st-year students enrolled at the Faculty of Psychology and Educational Sciences of Ghent University (Belgium) participated as a course requirement and for credit. None of them had taken part in any of the previous experiments. The participants were randomly assigned to one of two between-subjects conditions of a 2 (executive task: simple or choice RT) × 2 (condition: single and dual task) × 2 (fluency task: letter or category fluency) mixed design with repeated measures on the last two factors.

Materials. Letter and category fluency tasks were used. A letter fluency task requires participants to produce nouns or verbs beginning with a specified letter. Category fluency requires the participants to generate as many items as possible from a specified category (e.g., animals). In the present experiment, 14 fluency tasks were used: 8 letter fluency (4 nouns with N, A, K, B; 4 verbs with V, D, T, K) and 6 category fluency (flowers, fruits, animals, articles of clothing, names for girls, names for boys) tasks.

Procedure. The participants were seated at an 80486 PC with a 15-in. color monitor. The instructions were presented on the computer screen. Each participant performed the 14 verbal fluency tasks: 7 under a single task and 7 concurrently with either a simple or a choice reaction task, depending on which condition he or she was assigned to. The tasks were counterbalanced over the conditions contrasting single- and dual-task verbal fluency performance, with the two kinds of verbal fluency represented equally in both conditions. In other words, the 7 tasks in the control condition and the 7 tasks concurrently executed with either simple or choice reaction consisted of 4 letter (two nouns and two verbs) and 3 category fluency tasks that were counterbalanced over the conditions. Half of the participants started with the single-task verbal fluency tasks, and the other half with the dual-task conditions.

The fluency task was centered on the computer screen. After 2,000 msec, the word *start* flickered on the screen to signal the beginning of the verbal fluency task. At this point, the participants generated as many verbal items as possible within 45 sec. The words were taped by means of an audio recorder. The end of the fluency task was announced by a 100-Hz tone.

In the dual-task conditions, the simple or the choice reaction task was started 5,000 msec before the fluency task. After this single-task period, the task and the start signal were presented, following the same procedure, and from this point, both tasks were performed concurrently until the final sound. Each participant also performed the simple and choice RT tasks in a single-task condition for a period of 45 sec.

Results

The number of words produced per 45 sec as a function of the 2 (executive task: simple or choice RT task) × 2 (condition: single or dual task) × 2 (fluency task: letter or category fluency) mixed design was subjected to a repeated measures analysis based on the multivariate general linear model (see Table 1). The main effect of executive task was not significant [$F(1,22) = 1.33$, $p > .10$], whereas the main effects of condition and fluency task were [$F(1,22) = 30.82$, $p < .001$, and $F(1,22) = 49.08$, $p < .001$, respectively]. The interaction of executive task and condition was significant [$F(1,22) = 19.51$, $p < .001$], whereas the three-way interaction of executive task, condition, and fluency task was not ($F < 1$). Further planned comparisons revealed that the simple RT task affected neither letter fluency ($F < 1$) nor category fluency [$F(1,22) = 1.82$, $p > .10$]. In contrast, the choice RT task clearly affected both letter [$F(1,22) = 47.72$, $p < .001$] and category [$F(1,22) = 22.74$, $p < .001$] fluency. Finally, the absence of an interaction between the condition and fluency task factors in the choice RT task group ($F < 1$) shows that he choice RT task affected letter and category fluency similarly.

Discussion

The results of Experiment 3 show that the choice RT task interferes with verbal fluency, whereas the simple RT task does not. Since both RT tasks differ in terms of response selection demands, the conclusion that response selection affects verbal fluency is straightforward. The choice RT task effects were also considered separately for the letter fluency and the category fluency tasks. According to Rende et al. (2002), if response selection is mediated by a subsidiary component of WM, the choice RT task should differentially affect letter and category fluency performance. However, we observed that the decrement in fluency performance due to the concurrent choice reaction task was similar for the different variants of the fluency task. In other words, the choice RT task caused this more general impairment on verbal fluency, which has been observed with another executive secondary task (e.g., Rende et al., 2002). For these reasons, the findings in Experiment 3 support our hypothesis that response selection involves executive control in a way that does not involve any of the subcomponents of WM in a detectable manner. It is also important to mention that the simple RT task did not affect verbal fluency at all. An explanation for this finding will be given in the General Discussion section.

RESULTS OF RT TASK PERFORMANCE ANALYSIS

Performance on the simple and choice RT tasks was analyzed in order to investigate whether the RT tasks were also affected under dual-task conditions or, in other words, to make sure that our findings cannot be explained by dual-task tradeoffs. Because the dual-task analysis revealed a similar pattern of results in all three experiments, we decided to pool the three data sets.

The RT data show that both the simple and the choice RT task were affected under dual-task conditions. Performance on the simple RT task was delayed from 273 msec

Table 1
Mean Number of Words Produced per 45 Sec (With Standard Deviations) as a Function of Executive Task (Simple and Choice RT Tasks), Condition (Single and Dual Tasks), and Fluency Task (Letter and Category Fluency)

	Letter Fluency				Category Fluency			
	Single Task		Dual Task		Single Task		Dual Task	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Simple RT task	7.50	1.85	7.85	2.24	15.47	4.14	13.80	3.87
Choice RT task	9.23	2.23	5.77	1.65	15.75	3.06	9.86	2.18

(*SD* = 56.66) under single-task to 369 msec (*SD* = 93.55) under dual-task conditions. This 35% delay was statistically reliable [$F(1,108) = 184.91, p < .001$]. Similarly, performance on the choice RT task was delayed from 453 msec (*SD* = 73.01) under single-task to 530 msec (*SD* = 97.87) under dual-task conditions, a 17% delay, which was also statistically significant [$F(1,108) = 115.52, p < .001$]. The interaction of the simple versus choice RT task contrast and the single-task versus dual-task contrast was also significant [$F(1,108) = 6.49, p < .05$]. This shows that the dual-task effect on the simple RT task was stronger than that on the choice RT task.

From these analyses, it is clear that the dual-task setting affected both the primary memory tasks and the secondary RT tasks. This implies that no dual-task tradeoff occurred. The observation that the simple RT task was more adversely affected in a dual-task setting than the choice RT task was replicates earlier findings of Frith and Done (1986), who also observed a greater dual-task cost in RT performance for a simple (24%) than for a choice (8%) RT task. Such results are taken to indicate that simple and choice RT tasks follow different neural routes and, thus, are considered to be qualitatively different (see also Berns & Sejnowski, 1996; Rowe et al., 2000; Schubert, 1999). A final remark is related to the longer processing time observed in choice reaction than in simple reaction. This suggests that, in addition to the augmented executive demands, the increased processing time might also have contributed to the additional dual-task interference from response selection.

GENERAL DISCUSSION

The present study compared the patterns of dual-task interference of a simple and a choice RT task, to determine whether response selection involves executive control. Experiment 1 demonstrated that a choice RT task gives evidence of an executive pattern of dual-task interference with forward and backward verbal serial recall and that this interference is not produced at the level of WM's verbal slave system. Similarly, Experiment 2 demonstrated that, also in concurrent execution with forward and backward visuospatial serial recall, a choice RT task gives evidence of an executive pattern of dual-task interference and that this interference is not produced at the level of WM's visuospatial slave system. Finally, Experiment 3 demonstrated that a choice RT task causes additional interference with executive control, as compared with a simple RT task. Altogether, these findings show that response selection interferes with primary tasks that require executive control and that the interference is not produced at the level of the domain-specific verbal or visuospatial slave systems. Following the logic of the selective interference paradigm within a WM framework, this means that the response selection process involves executive control.

A point that requires some elaboration is the observation that in Experiments 1 and 2, the secondary task effects were obtained during the encoding and acquisition phase of a short-term memory task, whereas in Experiment 3, the effects were obtained during the retrieval of elements from long-term memory. This distinction is important because a number of studies by Naveh-Benjamin and colleagues have shown an asymmetry in attentional involvement between encoding and retrieval (e.g., Naveh-Benjamin, Craik, Guez, & Dori, 1998). They argued that "whereas encoding processes are controlled, retrieval processes are obligatory but do require attentional resources for their execution" (Naveh-Benjamin et al., 1998, p. 1091). These authors claim that encoding processes are consciously controlled and attention demanding. Retrieval processes, however, appear to be more protected, in the sense that under conditions of divided attention, the secondary task pays the entire dual-task cost. The present data fit well into this view of attentional involvement at encoding and retrieval. Our simple RT task affected the encoding of consonants and Corsi block positions, and although it did not hinder the retrieval of verbal fluency items, the RT task itself was clearly affected. The choice RT task severely impaired encoding in the verbal and visuospatial span experiments, and it also impaired the retrieval of verbal fluency items. The finding that choice reactions affect memory retrieval is not a new one (Carrier & Pashler, 1995; Rohrer & Pashler, 2003). However, it remains debatable whether the interference between response selection and retrieval originates from a structural bottleneck at response selection or from a shortfall in attentional resources when two attention-demanding tasks are simultaneously executed (see also Barrouillet, Bernardin, & Camos, 2004).

A further important matter with respect to the present results is the issue of task difficulty. It is a fact that a manipulation of cognitive processing affects the difficulty of a task, by which a potential confound for the interpretation of the results is induced. In this debate, a number of researchers have argued that *difficulty* cannot be put forward as a true alternative explanation for a manipulation effect, provided that the reason(s) for the differences in task difficulty are known. When the differences in task difficulty can be explained in terms of established qualitative processing differences, task difficulty becomes "merely a descriptor of a manipulation's consequence" (Garavan, Ross, Li, & Stein, 2000, p. 590). In this view, the theoretical and empirical developments supporting the view of qualitative processing differences between simple and choice RT tasks (Berns & Sejnowski, 1996; Frith & Done, 1986; Rowe et al., 2000; Schubert, 1999) make an alternative interpretation for the present findings, based on task difficulty, less plausible.

Finally, what are the implications of the present results for current views on executive functioning? First of all, although a few studies have already reported neuroimagery (Rowe et al., 2000) and electromyographic (Allain et al., 2004) findings suggesting that executive control is involved in response selection, the present study is the first to present converging evidence from a behavioral paradigm. In this sense, it supports the idea that executive control occurs at much more fundamental levels of human cognition than those initially proposed by means of higher level concepts, such as planning or problem solving. Second, the present findings also challenge the notion of a unitary executive controller, such as the central executive (Baddeley, 1996; Miyake et al., 2000). In this regard, we prefer to look at executive control as a concept that stands for the combined action of a number of processes (such as monitoring, inhibition, updating, and response selection), which are crucial for achieving an intended thought or behavior. Third, and maybe most important given the current lack of paradigms for the study of executive control (Barnard, Scott, & May, 2001), the present study has demonstrated that the selective interference paradigm seems to be a useful tool for investigating executive functioning. The potential of this paradigm for exploring other candidate executive processes awaits further exploitation.

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