Input monitoring and response selection as components of executive control in prosaccades and antisaccades

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Several studies have shown that antisaccades, more than prosaccades, are executed under executive control. It is argued that executive control subsumes a variety of controlled processes. The present study tested whether some of these underlying processes are involved in the execution of antisaccades. An experiment is reported in which two such processes were parametrically varied, namely input monitoring and response selection. This resulted in four selective interference conditions obtained by factorially combining the degree of input monitoring and the presence of response selection in the interference task. The four tasks were combined with a primary task which required the participants to perform either prosaccades or antisaccades. By comparison of performance in these dual-task conditions and performance in single-task control conditions, it was shown that antisaccades, but not prosaccades, were delayed when the secondary task required input monitoring or response selection. The results are discussed with respect to theoretical attempts to fractionate the concept of executive control.

Saccades towards a suddenly appearing peripheral stimulus (*prosaccades*) generally have short latencies (about 150–160 ms) and are performed with virtually no errors. In contrast, saccades in a direction opposite to a suddenly appearing peripheral stimulus (*antisaccades*) are much slower (about 220 ms or longer) and are error-prone (e.g., Hallett, 1978; Kristjánsson, Chen, & Nakayama, 2001; Roberts, Hager, & Heron, 1994; Stuyven, Van der Goten, Vandierendonck, Claeys, & Crevits, 2000).

Explanations of this difference assume that antisaccades are more complex than prosaccades. More specifically, prosaccades are automatically or exogenously triggered by the stimulus even though they can be controlled (e.g., they can be stopped, Logan & Irwin, 2000). Prosaccades are generally reflexive and can be triggered by a sudden change in the visual field, but they can also be endogenously controlled as when a prosaccade is performed in response to

a centrally shown arrow (Henik, Rafal, & Rhodes, 1994). In contrast, the execution of antisaccades requires at least two important subprocesses, namely the suppression of a reflexive saccade towards a visual stimulus and the execution of a saccade in the opposite direction. Several authors propose that there is a competition between these two processes. According to some authors, the prosaccade must be inhibited and then followed by a programmed saccade in the correct direction (Findlay & Walker, 1999; Hallett & Adams, 1980). Still others assume that prefrontal structures mediate the inhibitory control over antisaccades (Roberts et al., 1994). Recently, Massen (2004) has proposed an immediate competition between the more automatic prosaccade and the endogenously activated antisaccade.

Apart from these rather general statements concerning the differences between prosaccades and antisaccades, as pointed out by Everling and Fischer (1998), not much is known about the neural structures and processes involved in the generation of voluntary saccades (p. 895). Nonetheless, these authors show in their review of the literature, that it is quite likely that a large network of cortical and subcortical regions is involved in the generation of saccades. Evidence has been reported for the involvement of the superior colliculus, the substantia nigra pars reticulata, the caudate nucleus, the frontal eye fields, the supplementary eye fields, the cingulate gyrus, the insula, the parietal cortex, the globus pallidus, the

striatum and the thalamus. Even the anterior cingulate cortex and the prefrontal cortex seem to be part of the network. For most of these areas, their contribution in the generation of voluntary saccades remains unclear. There are not many robust findings and the results from single cell recordings, imaging studies and clinical work are often inconsistent. Although there are suggestions from single-cell recordings that the supplementary eye fiels may be involved in the suppression of prosaccades (Schlag-Rey, Amador, Sanchez, & Schlag, 1997), clinical studies have shown that the caudate nucleus and the substantia nigra pars reticulata is involved in the suppression of reflexive saccades (Everling & Fischer, 1998), while a study with transcranial magnetic stimulation has shown that the frontal eye fields are involved in saccade inhibition (Olk, Chang, Kingstone, & Ro, 2006). A recurring finding is that the prefrontal cortex, the frontal eye fields and the anterior cingulate cortex play an important role in the control of antisaccades.

Consistent with this general pattern of findings, many authors support the position that control over the generation of antisaccades is shared with executive functions (e.g., Eenshuistra, Ridderinkhof, & van der Molen, 2004; Nieuwenhuis, Broerse, Nielen, & de Jong, 2004). Several studies based on patients with executive dysfunctions have shown that their antisaccades suffer while their prosaccades are performed normally; this is the case in schizophrenics (Clementz, McDowell, & Zisook, 1994; Curtis, Calkins, Grove, Feil, & Lacono, 2001; Hutton et al., 2004; Klein, Heinks, Andresen, Berg, & Moritz, 2000; Manoach et al., 2002; Ramchandran et al., 2004), in prefrontal patients (Guitton, Buchtel, & Douglas, 1985; Pierrot-Deseilligny, Rivaud, Gaymard, & Agid, 1991), in parkinsonian patients (Briand, Strallow, Hening, Poizner, & Sereno, 1999; Crevits & De Ridder, 1997; Fukushima, Fukushima, Miyasaka, & Yamashita, 1994; Kitagawa, Fukushima, & Tashiro, 1994; MacAskill, Anderson, & Jones, 2002) and in patients with particular pervasive developmental disorders, such as attention deficit hyperactivity disorder, autism, tourette's syndrome, and others (Feifel, Farber, Clementz, Perry, & Anllo-Vento, 2004; Mostofsky, Lasker, Cutting, Denckla, & Zee, 2001; Mostofsky, Lasker, Singer, Denckla, & Zee, 2001; O'Driscoll et al., 2005). Also in normal development and aging, dissociations between pro- and antisaccades have been observed, (see e.g., Klein, 2001; Olincy, Ross, Youngd, & Freedman, 1997).

Experimental studies based on a dual-task methodology have also shown that antisaccades are more vulnerable to secondary task interference than prosaccades, especially when the secondary task puts an important load on working memory and executive control. In this vein, Roberts et al. (1994) have shown that antisaccades, but not prosaccades, are slowed and more often erroneous when a difficult concurrent arithmetic problem has to be solved. Using tasks taxing executive function without involving modality specific processing of the kind specified in the slave systems of the model of Baddeley and Hitch (1974), Stuyven et al. (2000) reported a similar pattern of results, and many other studies based on different methodologies corroborated the finding that antisaccades interact with working memory load and working memory capacity (e.g., Kane, Bleckley, Conway, & Engle, 2001; Mitchell, Macrae, & Gilchrist, 2002; Unsworth, Schrock, & Engle, 2004; Walker, Husain, Hodgson, Harrison, & Kennard, 1998).

The hypothesis that the behavior of antisaccades is governed by executive control does not clarify how these saccades come to be slower or more error-prone. The notion of executive control is rather vague and often used as a substitute for control processes or functions, such as planning, inhibition, resistance, and others (e.g., Burgess, 1997). Recently, the unitary construct of executive functioning and the related notion of a "central executive" system has been questioned and several researchers have in fact proposed ways to redefine executive control as a family of interrelated processes or functions, such as dual-task coordination, task-switching, interference control and manipulation of information in long-term memory (e.g., Baddeley, 1996; Miyake et al., 2000).

A slightly different approach can be taken by thinking of executive control *as emerging from the interaction between intentional and nonintentional processes.* More specifically, executive control concerns the processes that are required to set up, maintain, perform, change, interrupt, and finish particular tasks. Each such a task corresponds to an action or a sequence of actions intentionally selected for execution. In order to perform the task, the task goal and possibly also its subgoals must be maintained in working memory until execution is complete. Together with the task-goal, also a number of task execution constraints, such as the stimulus-response translation rules, timing constraints, output modality, and so on, have to be kept active in working memory (as is demonstrated by recent findings in task switching research, e.g., Schuch & Koch, 2001; Philipp & Koch, 2005). The representation of the task goal(s) and the task constraints together are often termed the *task-set*, i.e., the collection of all the task parameters that come into play to select, control, and monitor the actions that are engaged to achieve the goal. Attentional resources are needed to keep

this task-set active, to replace a task-set when another task has to be performed (Meiran, 1996, 2000; Rogers & Monsell, 1995) and to select, control and monitor the activated representations. This also includes error monitoring (e.g., Botvinick, Cohen, & Carter, 2004) and interference control (e.g., Derrfuss, Brass, & von Cramon, 2004; Rushworth, Hadland, Gaffan, & Passingham, 2003).

As already pointed out, some processes that are deployed in the achievement of a task goal require attentional resources while others run off more or less automatically once triggered. Based on current knowledge, it is not clear which processes consume attentional resources. Previous research has suggested that executive control may manifest itself in more specific processing components. Looking at executive control via these more elementary processes yields several advantages. First, each processing component is studied separately from the others and may or may not reveal dual-task interference with a particular primary task. This allows conclusions about the degree to which that primary task involves the processing component studied. Second, when a particular processing component sometimes does and sometimes does not interfere with a range of primary tasks, this may contribute to a useful fractionation of the vague concept of executive control. Finally, this may result in a profile of the executive processing components involved in a particular primary task.

The approach advocated here differs in some important respects from the fractionation proposed by Baddeley (1996) and Miyake et al. (2000). Whereas the fractionation proposed by these authors attempts to define a partitioning in terms of functions and tasks, the present approach aims at the level of processing components that may be involved in many different tasks. One of the proposed componential processes is response selection. This component may be involved in task switching, inhibition and in memory updating. Although a similar methodology is used, the present approach tries to discover component processes that play an important role in several executive tasks.

Thus far, three processing components have received some attention in recent research. This is the case for input monitoring, response selection and memory updating (see e.g., Vandierendonck, 2000a, 2000b). These are by no means the only processing components involved in executive control, but they constitute a subset of processes that are easy to implement in a typical selective interference design. Other components, such as response inhibition (e.g., Logan & Cowan, 1984; Logan & Irwin, 2000; Verbruggen, Liefooghe, Szmalec, & Vandier-

endonck, 2005) and conflict monitoring (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Botvinick et al., 2004) have been intensively studied in different kinds of paradigms.

The degree of *input monitoring* relates to the amount of time attention has to be directed towards input processes to detect events that are relevant or even important for the current task. If attention is continuously directed towards the information input, detection of the critical events will probably occur without errors, but this also implies that less attentional resources are left for the other task components and for other concurrently operated tasks. Therefore, the resources will be shared by switching attention between the different competing processes. On this basis, it is expected that when a task requires a higher degree of input monitoring, more attentional resources will be consumed by input monitoring at the expense of the other task components and concurrent tasks.

The notion of *response selection* or *stimulus-response translation* concerns the selection of an appropriate response given the stimulus and the task-set. This process requires attentional resources because stimuli are often associated with many responses which may become activated. Many of these activated responses, however, are not consistent with the current task goal, the current stimulus-response mapping and/or the current response modality, etc. Therefore, it is necessary that the correct response is more active than the other ones so that it wins the competition. This can be achieved by increasing the activation of the correct response or by suppression of the activation of the incorrect ones (or both). Evidence from several sources converges on the idea that response selection consists of two components, response activation and response choice (Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002; Lien & Proctor, 2002). The evidence also indicates that response selection involves inhibition of incorrect alternatives (Allain, Carbonnell, Burle, Hasbroucq, & Vidal, 2004; Carbonnell, Hasbroucq, Grapperon, & Vidal, 2004), and that more efforts are required for a response selection when the stimuli eliciting the alternative response are more similar (Nieuwenhuis, Yeung, & Cohen, 2004; Szmalec, Verbruggen, De Baene, & Vandierendonck, 2005). Taken all together, it may be concluded that there is a growing body of evidence that indicates that the process of response selection requires attentional resources to make sure the correct response is chosen. Therefore, all other things being equal, it may also be expected that when two concurrent tasks involve response selection the competition for attentional resources will

be much more important than when only one of the tasks involves a response selection.

The third proposed process, *memory updating*, concerns control over the changes in working memory contents that are required with changes in the task execution. This is typically involved in running span tasks, i.e., tasks requiring recall of the last n elements in sequences with variable length (Van der Linden et al., 1999) and in n-back tasks, i.e., tasks where an element n positions earlier has to be recalled (Morris & Jones, 1990; Smith & Jonides, 1997) and it seems quite likely that this also involves some form of interference control (Szmalec & Vandierendonck, 2005). Memory updating is probably also involved in task-set switching and in the selection of appropriate strategies on a trial-by-trial basis.

All three processing components have already been the focus of studies investigating whether these components indeed consume attentional resources. Thus far, only one published study has supported the idea that input monitoring calls on attentional resources (Vandierendonck, De Vooght, & Van der Goten, 1998), while several studies have shown that response selection always seems to compete for attentional resources (e.g., Deschuyteneer & Vandierendonck, 2005a, 2005b; Deschuyteneer, Vandierendonck, & Muyllaert, in press; Deschuyteneer, Vandierendonck, & Coeman, 2005; Szmalec, Vandierendonck, & Kemps, 2005). Also memory updating seems to consume important amounts of attentional resources (e.g., Deschuyteneer et al., in press, 2005; Szmalec & Vandierendonck, 2005).

The present study focuses on the role of two of these processes in pro- and antisaccades, namely input monitoring and response selection. On the basis of previous research results which show a difference in the extent to which prosaccades and antisaccades are executively controlled, specific predictions may be formulated with respect to the components of input monitoring and response selection. It is clear from the above that prosaccades are events triggered by a peripheral stimulus and are often running off almost automatically. However, as mentioned in the introduction, they can be endogenously controlled, which seems to occur especially when the saccades are predictable. Given that in experimental designs, the prosaccades are rather unpredictable, as both the saccade timing and the saccade direction are randomly chosen, it is quite likely that prosaccades produced under such conditions are reflexive. As a consequence, such prosaccades probably do not need a fully specified task-set for their execution. If this is correct, response selection is not required as the response is automatically performed without much ex-

ecutive control. It is predicted therefore, that the presence of response selection in a concurrently executed task will not affect the efficiency of prosaccade execution. For a prediction about the effect of input monitoring, it may be considered that prosaccades require detection of stimulus changes. Hence, prosaccades will call on attentional resources to succeed in fast stimulus detection, but as the task-set representation does not require many resources, it is expected that the competition for these resources between the prosaccade task and the secondary task will not result in an impairment of prosaccade performance. Because the dual-task situation involves a simultaneous coordination of two task-sets, it is expected, though, that a general dual-task coordination cost is observed because both task-sets must be maintained and handled concurrently.

In contrast, antisaccades are performed completely under cognitive control since the prosaccade must be suppressed and a saccade in the opposite direction must be programmed. Because of that, a task-set has to be set up with particular constraints. In conditions where concurrently with the antisaccade task a response selection has to be performed, the two tasks will compete for the same attentional control resources and/or mechanisms and this should result in a slowing of the execution of the antisaccades. In conditions where the antisaccade task is performed concurrently with a secondary task that puts a higher load on scanning and inspecting the input for the occurrence of rather unpredictable events, this probably will introduce a competetion with the detection of the primary-task stimulus which is also not completely predictable. Therefore, it may be predicted that a secondary task that puts a higher load on input monitoring will interfere more with performance on the antisaccade task and more so than with the prosaccade task because the processing load of prosaccades is smaller. Hence, it is predicted that under dual-task conditions both input monitoring and response selection will impair the efficiency of antisaccade execution. As with the prosaccade task, also a general dual-task coordination cost is expected.

For the test of our hypotheses a specific methodology is required in which the processing components, input monitoring and response selection are operationalized by appropriate secondary tasks. This methodology is based on the usage of simple secondary tasks that differ only in relevant ways from each other. The underlying assumptions are that each task may call on a variety of processes and that a task is never process-pure. Inferences about specific processes can only be made by comparing the effects of tasks that differ from each other in specific

ways. Therefore, we selected simple tasks that allow these comparisons to be made. In the present study, simple secondary tasks were used which are based on a continuous stream of more or less predictably occuring stimuli to which a fast response is required. The reaction-time (RT) tasks are either simple RT or choice RT tasks. In simple RT tasks, a response can be emitted as soon as a stimulus is detected, whereas in choice RT tasks the stimulus must be identified so as to select the corresponding response. Over the years a body of evidence has been accumulated in support of the view that a choice RT task involves the process of response selection, while a simple reaction task does not (e.g., Frith & Done, 1986; Schubert, 1999). Hence by comparing performance on the primary task (saccades) in a condition with simple reaction tasks and in a condition with choice reaction tasks, the importance of response selection can be inferred. By varying the predictability of the tasks in the stream, the degree to which attention is recruited by the stream of tasks can be varied. When the tasks come in a fixed pace, that means with fixed interstimulus intervals, the occurrence of each stimulus can be exactly predicted. If, on the contrary, the pace varies with shorter and longer inter-stimulus intervals being selected at random, more attention is needed for detecting the stimulus and hence the process of input monitoring would be required more often or too a larger degree than in the conditions with a fixed pace. Again, the importance of input monitoring can be estimated by comparing primary task performance in conditions with lower and with higher degrees of input monitoring present in the secondary task.

It is clear that the two variations (presence or absence of response selection and degree of input monitoring) can be implemented independently in a factorial design. Therefore, in both experiments all participants were tested in five conditions: a control (only saccade task) and four dual-task conditions in which the saccade task was performed concurrently with one of the four possible secondary tasks. These were, simple reaction task with fixed pacing (SRT-F), simple reaction task with random pacing (SRT-R), choice reaction task with fixed pacing (CRT-F) and choice reaction task with random pacing (CRT-R). Additionally, the participants were also tested in each of the secondary tasks alone, in order to enable a test of possible dual-task trade-offs.

These predictions were tested in a between-participants experiment. Half of the participants performed the prosaccade task in two sessions under five different conditions (control and four dual-task conditions: SRT-F, SRT-R, CRT-F and CRT-R). The other half of the participants performed the antisaccade task in two sessions under the same conditions. As explained above, we predicted that neither input monitoring nor response selection would interfere with prosaccade performance and that both would interfere with antisaccade performance. Additionally, we expected a nonspecific dual-task cost due to the requirement to execute two tasks simultaneously in both prosaccades and antisaccades.

Method.

Participants and Design. Fourty persons (7 male) participated in this study. They were all volunteers, 12 of them participated for course credit and 28 were paid for their participation. All participants had normal or corrected vision. The mean age was 21.8 years (SD 3.06; range 19–30 years). They all participated in two experimental sessions of about 75 minutes each. Half of the participants were assigned to the prosaccade sessions, the other half performed the antisaccade sessions.

Materials and procedure. Eye movements were recorded by a Senso-Motoric Instruments (SMI Eyelink) video-based pupil tracking system. The sampling rate of the Eyelink system was 250 Hz. Viewing was binocular but eye movements were recorded from the right eye only. A high-speed video camera was used for recording. It was positioned underneath the monitored eye and held in place by head-mounted gear. Participants were seated at a distance of ± 70 cm from the display and a chin rest was used to reduce head movements during the experiment. The initial calibration and validation of the eye-tracking system generally required approximately 10 minutes and consisted of a standard 9-point grid. This drift correction procedure of the Eyelink system was repeated before each condition of the experiment.

Each participant completed two sessions on different days, consisting of three conditions each: in the first session a control condition and two dual-task conditions, and in the second session a control condition and the two remaining dual-task conditions. Participants were randomly assigned to a particular order of sessions and within each session the order of the conditions was randomized. Both sessions began with a block of nine practice trials. Conditions consisted of ten blocks of nine trials and before each dual-task condition, participants performed a block of nine practice trials combined with the appropriate secondary task. After each block a calibration check (with a single fixation point in the centre of the screen) was

performed. Before each of the two sessions single-task performance on the secondary tasks used in this session was measured.

Throughout, participants were required to perform either prosaccades or antisaccades in response to a visual stimulus. Each trial started with the presentation of a fixation sign, a white dot, in the centre of a black computer screen. After 2 to 3.5 s this fixation sign disappeared as soon as the software registered a stable fixation on it. The fixation sign was subsequently replaced by a white rectangle of $1.8°$ horizontally by $0.7°$ vertically at $7.3°$ on the left or right side of the centre. In the prosaccade conditions, the participants were told to look as fast as possible at the rectangle until it disappeared and the fixation point reappeared in the centre of the screen. This happened after an interval between three and five seconds. In the antisaccade conditions, the participants were told to perform a saccade as fast as possible in the opposite direction to the complementary position of the rectangle.

The saccade tasks were performed in five conditions, one control condition in which the saccade task had to be performed alone and four dual-task conditions. In the dual-task conditions the saccade task was combined with four secondary tasks, more specifically a fixed and a random simple RT task (SRT-F and SRT-R respectively) and a fixed and a random two-choice RT task (CRT-F and CRT-R respectively). In the simple RT tasks, participants had to hit a key as fast as possible each time they heard a tone. The tones had a frequency of 262 Hz and lasted for 200 ms. In the SRT-F task, the tones were presented at a fixed rate with an interval of 1200 ms between successive tones. In the SRT-R task, the interval between the tones was randomly selected among the values of 900 and 1500 ms. In the two-choice RT tasks, low (262 Hz) and high (524 Hz) tones were presented and each time they heard a tone, participants had to press a corresponding key on a response box connected to the computer. The presentation schedule of the tones was fixed (every 1200 ms) in the CRT-F condition and random (every 900 or 1500 ms) in the CRT-R condition. In the dual-task conditions the presentation of the tones started 5 seconds before the presentation of the first visual stimulus. Moreover, the two streams of events (visual stimuli in the primary tasks and auditory stimuli in the secondary tasks) were programmed to occur independently from each other. Only when two stimuli collided in time, the stimuli were presented sequentially, one following immediately after the other one.

Results. The data were analysed on the basis of a repeated measures analysis by means of the multivariate general linear model. The tests for significance assumed an α-level of .05, unless otherwise mentioned. Trials that differed from the participant's condition mean by more than 2.5 standard deviations were categorized as outliers and excluded from the analysis. Also incorrect trials were excluded. The dependent variables in this study were saccade latency and accuracy. Saccade latency was defined as the time between stimulus onset and saccade onset. Accuracy was measured as the execution of the saccade in the instructed direction without taking into account the distance from the target position. This way three kinds of errors can be distinguished: direction errors (performing a saccade in the other direction), anticipations (starting the saccade before the fixation sign disappeared) and failures to start the saccade. The latter two types of errors were very rare.

Latency. First, a 2 (Saccade task: prosaccade or antisaccade) $\times$ 5 (Conditions: control and four dual-task conditions) design was applied with repeated measures on the last variable. Order of conditions within the sessions was added as a covariate defined by four dummy variables. Figure 1 displays saccade latency as a function of task and the five conditions of the experimental design. As expected, prosaccades were faster ($M = 173$ ms) than antisaccades ($M = 276$ ms). The analysis revealed main effects of saccade task, $F(1, 30) = 106.09$ and condition, $F(5, 26) = 27.04$. To test for the magnitude of the nonspecific dual-task coordination cost, the contrast between the control condition ($M = 198$ ms) and the SRT-F condition ($M = 226$ ms) was used. The reason for this choice is that the latter selective interference condition did not involve response selection and had the lowest degree of involvement of input monitoring. The contrast was significant, $F(1, 30) = 72.35$, suggesting that there was indeed a nonspecific dual-task coordination cost. The coordination cost was larger in the antisaccade task ($M = 47$ ms) than in the prosaccade task ($M = 11$ ms), $F(1, 30) = 26.31$.

An analysis based on the four dual-task conditions according to a 2 (Saccade task) $\times$ 2 (Response task: simple reaction versus two-choice reaction) $\times$ 2 (Presentation schedule: fixed versus random) design, with repeated measures on the last two effects and order of conditions as covariate revealed that the main effects of saccade task, $F(1, 30) = 111.10$, and of response task, $F(1, 20) = 12.23$, reached significance. Prosaccades ($M = 179$ ms) were faster than antisaccades ($M = 297$ ms) and saccades were faster in the
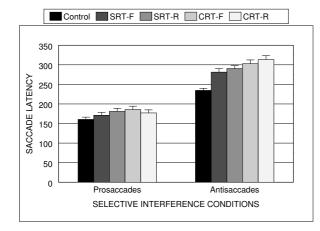
Figure 1: Latency of pro- and antisaccades in the four conditions obtained as a function of the factorial combination of input monitoring and response selection and in a fifth control condition. The whiskers represent the standard error of the mean.

simple RT ($M = 231$ ms) than in the choice RT condition ($M = 245$ ms). The main effect of presentation schedule (M respectively 235 and 241 ms for fixed and random presentation) was not significant, $F < 1$, and it did not interact with response task, $F < 1$. Saccade task interacted with both response task, $F(1, 30) = 7.21$, and presentation schedule, $F(1, 30) = 4.51$, and the triple interaction of saccade task, response task and presentation schedule failed to attain significance, $F(1, 30) = 1.25$, $p = .27$.

In this design, type of response task compares simple and choice RT tasks and thus indicates the effect of response selection; presentation schedule compares predictable and random presentation schedules and is thought to capture the effect of input monitoring. Given the main effect of response task and its interaction with saccade task, an analysis per saccade task revealed that the effect of response task was not significant in prosaccades (176 vs. 181 ms), $F < 1$, while it was in antisaccades (286 vs. 308 ms), $F(1, 15) = 15.50$. Similarly, the effect of presentation schedule (178 vs. 179 ms) was not reliable in prosaccades, $F < 1$, but it was in antisaccades (292 vs. 302 ms), $t(15) = 2.06$, according to a one-tailed test. Neither in the prosaccade, nor in the antisaccade condition, the interaction of response task and presentation schedule attained significance, respectively $F(1, 15) = 1.06$ and $F < 1$.

Accuracy. Overall, accuracy (proportion correct) was very high. Therefore, the analyses were based on arcsinus transformations of the data. Pro-

portions of correctly performed saccades are displayed in Table 1 as a function of the Saccade task × Condition design. Only the main effect of saccade task was significant, $F(1, 30) = 59.19$ with lower accuracy in antisaccades (.79) than in prosaccades (.95). The main effect of condition failed to attain significance and did not interact with task, and neither did the difference between the control condition (.89) and the SRT-F condition (.87).

In the analysis based on a 2 (Saccade task) × 2 (Response task) × 2 (Presentation schedule) design with repeated measures on the last two effects, only the effect of saccade task was significant (.95 for prosaccades and .78 for antisaccades), $F(1, 30) = 52.08$. None of the other effects or interactions attained significance (largest $F(1, 30) = 1.91$, $p = .18$.

Separate analyses per task condition confirmed these results. Neither in the prosaccade nor in the antisaccade condition, any of the effects or their interactions attained significance. The contrasts between the control condition and the SRT-F condition also failed to attain significance, both $F < 1$.

The errors committed can be considered per category. In the context of antisaccades in healthy people it is most meaningful to inspect the directional errors. These errors were rare in prosaccades (less than 1% of the trials), but were clearly present in the antisaccade conditions (18% of the trials on average). As can be seen in Table 1, these errors did not vary in a systematic way over the conditions. A multivariate analysis of variance with order of conditions as a covariate, did not reveal any effects of response task, presentation schedule or their interaction. Possible reasons for this absence of effects will be proposed in the Discussion section.

Secondary task performance. Performance on the secondary tasks was also recorded both in single-task and in dual-task conditions. For all four secondary tasks, the analysis included reaction times, standard deviations of the reaction times and proportion of errors. The first two measures were analysed on the basis of a 2 (Task: prosaccade or antisaccade) × 2 (Response type: simple versus choice) × 2 (Presentation schedule: fixed versus random) × 2 (single versus dual-task condition) factorial design with repeated measures on the last three effects and with order of conditions as a covariate. Since errors were only meaningful in the choice RT task, the same design without the effect of response type was used.

The resuls of the reaction time analysis are reported slightly more extensively than those of the other measures. Secondary task performance was faster in

Table 1: Means and standard deviations of the proportion of correctly performed saccades and of the proportion of directional errors in antisaccades as a function of the five task conditions

	C	SRT-F	SRT-R	CRT-F	CRT-R
Prosaccades					
M	0.97	0.96	0.96	0.95	0.93
SD	0.03	0.04	0.03	0.05	0.07
Antisaccades					
M	0.80	0.78	0.79	0.80	0.76
SD	0.11	0.16	0.13	0.14	0.15
Antisaccades; Directional Errors					
M	0.18	0.19	0.19	0.16	0.19
SD	0.10	0.15	0.12	0.12	0.13

the single-task ($M = 330$ ms) than in the dual-task conditions ($M = 392$ ms), $F(1,30) = 50.91$. The simple RT task was faster ($M = 311$ ms) than the choice RT task ($M = 411$ ms), $F(1,30) = 96.22$. However, the effects of saccade task and of fixed versus random presentation schedule were not significant, both $F < 1$. There was an interaction, though, of RT task and presentation schedule, $F(1,30) = 4.89$. No other interactions were significant.

For the other measures, there was also a better performance in the single-task than in the dual-task conditions, with smaller standard deviations of the reaction times in single-task ($M = 96$ ms) than in dual-task conditions ($M = 173$) ms), $F(1,30) = 109.68$; and with fewer errors in single-task ($M = 0.04$) than in dual-task conditions ($M = 0.08$), $F(1,30) = 8.09$.

Even though the single-task conditions always preceded the corresponding dual-task conditions, performance was better in the single-task conditions. In fact, order of testing and single-versus-dual-task are confounded here. However, the difference between performance in the two conditions was so large, that it is unlikely that these effects are due to the order in which these conditions were executed. Moreover, the observation that dual-task performance was slower, more variable and more error-prone than single-task performance is consistent with the hypothesis that the two tasks were competing for the same resources.

We also calculated correlations between the saccade latencies and reaction times on the secondary task in the dual-task conditions, in order to check for the presence of a dual-task trade-off. These correlations were $-.14$, $.01$, $.05$, and $.26$ for respectively the SRT-F, SRT-R, CRT-F and CRT-R task. Only one of these correlations was negative and it did not attain statistical significance ($p = .37$).

Discussion

The present findings can be summarized as follows. First, antisaccades were performed slower and with more errors than prosaccades. This finding is consistent with previously reported findings (e.g., Roberts et al., 1994; Stuyven et al., 2000). Second, saccades were executed faster in the single-task condition than in the easiest of the dual-task conditions. This indicates the presence of a nonspecific dual-task coordination cost. Third, saccade execution was slowed down in conditions where the secondary task required a response choice in contrast to the other dual-task conditions. However, this effect interacted with saccade task and decomposition of this interaction showed that this effect occurred in antisaccades but not in prosaccades. This indicates that response selection plays a role in antisaccade performance. Fourth, overall saccade execution was not slowed down as a function of variations in the presentation schedule of the secondary tasks, but this effect interacted with saccade task and a further analysis showed that presentation schedule affected saccade performance in antisaccades and not in prosaccades. This contrast is taken to indicate the role of input monitoring and the findings seem to suggest that input monitoring plays a role in antisaccades but not in prosaccades. Fifth, the effects of response task and presentation schedule did not interact. Sixth, error rates did not vary as a function of the dual-task manipulations. Seventh, there were no indications of a dual-task trade-off.

With respect to the role of *response selection*, the reaction time findings confirm the predictions. Since the procedure favoured prosaccades to be triggered exogenously, only a limited amount of executive control is needed for their preparation, initiation or execution. According to our hypothesis, response selec-

tion is one of the processing components involved in executive control and therefore there was no reason to expect that the presence of this processing component in the concurrent secondary task would interfere with the processing stream of the primary task, the prosaccade task. Antisaccades, on the contrary, require more executive control. Therefore, we reasoned that common attentional resources would be needed for the response selection required in the primary task and for the response selection in the secondary task. Because of the concurrent nature of the tasks, some degree of temporal overlap is expected to occur and this would result in a larger degree of competition for the same resources with as a result a slowing of both the antisaccades and the secondary task responses.

It could be argued that a similar effect should be observed in terms of accuracy. In particular, directional errors which are based on a failure to perform a correct response selection could be expected to vary with the presence of response selection in the secondary task. In fact, except for the difference between pro- and antisaccades, the accuracy data did not reveal any effect at all. Presently, the question may be raised why no main effects were observed in the accuracy data. One possible reason may lay in the statistical power of the present experiment: participants performed five conditions, so that the number of events studied per condition (30) is less than usual. Another reason may be found in the fact that pro- and antisaccades were not mixed. As shown by Massen (2004), in a mixed design, anti-saccade errors decrease with the probability of an antisaccade in the block (see also Koval, Ford, & Everling, 2004). In other studies using a blocked design (e.g., Stuyven et al., 2000), similarly, the effects of modulations of a secondary task load were only present in the latencies. Still another reason may be related to the extensive testing procedure used in the present study. Hallett (1978) already reported that the error rate of antisaccades dropped dramatically with practice. This was also the case in the present study with many errors initially in the first antisaccade session. Since the order of the experimental conditions was counterbalanced, this effect was neutralized and the error rate would probably have been higher and possibly also more variable in a design with less practice. Usage of a between-subjects design for the experimental effects is not a viable alternative, however, because between-subjects comparisons have less power.

The conclusion that response selection interfered with antisaccade performance because response selection is part of the executive control processing stream, is also consistent with other findings in the literature. Several selective interference studies have already demonstrated the executive nature of response selection. Szmalec et al. (2005) found that concurrent response selection interferes with verbal fluency tasks and that the pattern of interference in short-term memory tasks is different from that of modality-based interference tasks such as articulatory suppression and visuospatial matrix tapping. With simple mental arithmetic as the primary task, Deschuyteneer and colleagues (Deschuyteneer & Vandierendonck, 2005a, 2005b; Deschuyteneer et al., in press, 2005) similarly found that concurrent response selection impaired performance on simple arithmetic sums, products, subtractions and divisions. Moreover, as pointed out in the introduction, many other studies present evidence on the controlled nature of response selection. The present study is the first one to show that response selection is an important factor mediating voluntary saccades. It may be pointed out, however, that the task used by Stuyven et al. (2000) quite likely involves both response selection and input monitoring as major components (cf. Vandierendonck, 2000b). A similar point may be developed for the work of Roberts et al. (1994). As they used mental arithmetic as a secondary task, no direct motor responses were requirements, but the research of Deschuyteneer and Vandierendonck (2005a, 2005b) shows that response selection plays a prominent role in mental arithmetic.

Also with respect to *input monitoring*, the results confirmed the predictions. Because input monitoring is assumed to be part of the executive control stream to the extent that attentional resources are required to scan the environmental input, we expected an impairment of antisaccade performance and to a lesser extent of prosaccade execution. This prediction was also confirmed: antisaccades but not prosaccades were slowed more when the degree of input monitoring in the concurrent secondary task was increased. This finding further indicates that input monitoring recruits the same attentional resources in the primary (saccade) task and in the secondary tasks. In particular, as already pointed out in the introduction, both the antisaccade task and the secondary tasks with variable interstimulus intervals involve stimuli occurring at a rate that is not completely predictable. In order to perform well on both tasks, participants need to pay attention to two different streams of environmental events, both of which require a rapid response. It seems obvious that the same set of attentional resources and possibly a common set of processes is involved in executing both tasks simultaneously. This results in a suboptimal allocation of resources with a slowing of the responses in both tasks as a consequence. Again, the present study is the first one

to explicitly demonstrate the role for attention related monitoring processes to play a role in saccade tasks. As was already pointed out, input monitoring may have been a factor in the method used by Stuyven et al. (2000). This also relates to findings showing that predictability of saccades is an important factor affecting the efficiency of saccade performance, as shown by several research groups (e.g., Koval et al., 2004; Massen, 2004; O'Driscoll et al., 2005). It is interesting to note that in several studies with more complex cognitive primary tasks (mental arithmetic) input monitoring was not found to impair performance (Deschuyteneer & Vandierendonck, 2005a, 2005b; Deschuyteneer et al., in press, 2005).

Why then does the same not occur in prosaccades? In our view, prosaccades do not need a fully elaborated task-set configuration as they are performed mostly automatically in these blocked unpredictable prosaccade design. For this reason, the prosaccade task-set representation does not require many resources and therefore the competition for these resources between the prosaccade task and the secondary task do not result in an impairment of prosaccade performance. It is important to stress that with voluntary prosaccades based on endogenous cueing (e.g., arrows indicating the direction of the eye movement Henik et al., 1994), we expect that a fully elaborated task-set configuration is made and kept active. As a result, interference with these prosaccades would be expected, although the degree of efficiency impairment may be smaller because in this case no inhibition of reflexive saccades is required.

Because of the factorial design of the experiments, it was possible to study the effects of response selection and input monitoring separately, and it was also possible to test the *independence of both processing components*. As the interaction of the two manipulations was not significant, it seems obvious that in the combination with an antisaccade task, the effects of the two components where achieved independently from each other. This is also consistent with the locus of the effects as described above: while input monitoring is assmued to achieve its effect in early processing stages (stimulus detection), the effect of response selection is supposedly situated at later processing stages nearer to the response. On this account, the effects occurred at different processing stages and therefore an interaction was not to be expected.

The present study also found a rather large nonspecific dual-task coordination cost. This cost was present in both experiments but in the latency data only. Although such a cost was expected, it appeared to be rather large. This is consistent with findings reported in the literature. Several studies have shown that the requirement to perform two tasks simultaneously, as in dual-task and selective interference studies, or in close alternation, as in alternating list and alternating runs designs in task switching (e.g., Rogers & Monsell, 1995; Spector & Biederman, 1976), results in a cost. The requirement for the participants to perform two spatial motor tasks simultaneously may have contributed to the size of the effect. Other dual-task studies often have used tasks that do not require a spatial response concurrently with the saccades (e.g., Roberts et al., 1994) while still others did use tasks that allowed participants more freedom in scheduling the processes of the two tasks (e.g., Stuyven et al., 2000). It is also possible that the fact of being part of a dual-task setup encourages the participants to do the tasks more carefully by slowing down responding, particularly the more controlled tasks.

Dual-task studies sometimes suffer from dual-task trade-offs. It may happen that the primary task is impaired but that at the same time, the secondary task is performed better than in a single-task control condition. This was also checked. Interestingly, and as expected, performance decrements were observed in both tasks and the correlations between primary and secondary task performance did not reveal any signs of a trade-off.

Taken all together, the present results lend further support to the view that it is possible to redefine executive control in terms of more restricted processing components that are more readily accessible for experimental testing. In particular, the present study shows that the processing components of response selection and input monitoring are part of this executive control stream as they did impair controlled eye-movements (antisaccades) but did not affect the more automatic eye-movements (prosaccades). Moreover, the effects of the components were independent from each other, probably because their interference was produced at different stages of the primary task. For sure, these two components are not the only ones involved in executive control and future research will have to clarify which other components are present in eye-movement control. In this respect, memory updating (e.g., Mitchell et al., 2002) and inhibition (e.g., Hamilton & Martin, 2005) provide promising avenues for further research. Importantly, all these components may be linked to neural activity in particular brain areas, in particular the dorsolateral prefrontal cortex and the anterior cingulate cortex, which recently appeared to be crucial areas in brain leasion studies (e.g., Pierrot-Deseilligny, Muri, Nyffeler, & Milea, 2005; Ploner, Gaymard, Rivaud-Péchoux, &

Pierrot-Deseilligny, 2005). To some extent, the dorsolateral prefrontal cortex may also be involved in spatial working memory (Pierrot-Deseilligny et al., 2005) especially as it has been shown that abrupt eye-movements disrupt spatial working memory representations (Pearson & Sahraie, 2003).

By using an approach oriented at decomposing executive control into more specific processing components, the present study replicates previous findings concerning the role of executive control in guided eye movements and shows that antisaccades involve at least two different stages of controlled processing. At the same time, the study provides evidence for the involvement of the components of input monitoring and response selection in executive control and it adds further confidence that the attempts at fractionating executive functioning may help to come to a better understanding of which processes are and which processes are not playing a role in executive control.

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