

EXECUTIVE FUNCTIONS AND TASK SWITCHING

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In the last decade, the task switching paradigm has been rediscovered as a tool to investigate executive functions. The article presents an overview of experimental research on task switching. Special attention is given to the findings with respect to task switching costs that remain after a rather long preparation interval, the residual switch costs.

Executive Function

Over the past few decades, the interest in executive functions has been growing, both in cognitive psychology and in neuropsychology. Already for some time, neuropsychologists have been trying to gain insight in the origins of the prefrontal syndrome. The crucial problem they are facing is related to the validity and reliability of the neuropsychological tests used to assess the dysexecutive syndrome (Rabbitt, 1997). Validity is a problem because the syndrome is ill-defined and multifaceted. Executive control is required in many situations, among others in situations that involve planning and decision making, in situations that involve error correction or trouble shooting, in situations where well-learned responses are lacking, in dangerous or technically difficult situations and in situations that require the overcoming of a strong habitual response or that require resistance to temptation (Burgess, 1997, p. 84). Although all these aspects are quite typical of the dysexecutive syndrome, most patients will fail only in some of the situations listed. Consequently, a test which is sensitive to a particular deficit (e.g., planning) may be insensitive to other deficits (e.g., inhibition). For these reasons, low correlations are expected between tests in a sample of prefrontal patients. Moreover, many so-called frontal tests share features with problem-solving and intelligence tests, which leads some scholars to propose that executive function is nothing but Spearman's *g* (see e.g., Sternberg, 1985). Yet there is evidence against this view (e.g., Ardila, Pineda, & Rosselli, 2000; Crinella & Yu, 2000).

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There is, however, not only a problem of validity, but also one of reliability. A patient with a prefrontal deficit is still capable of learning. Consequently, assessment of the deficit with a particular test is bound to show a low test-retest correlation because of learning and adaptation between successive testing occasions. For that reason, it is often stressed that neuropsychological tests of executive function should be novel (see e.g., Phillips, 1997). Often, though, a test is novel the first time only.

On the part of cognitive (experimental) psychology the growing interest in executive functions originates, among others, from research in the structure and functioning of working memory inspired by the working memory model proposed by Baddeley and Hitch (1974). This model proposes that the architecture of working memory comprises two slave systems, one for short-term maintenance of phonological information and a similar one for visuo-spatial codes; these two slaves are controlled and co-ordinated by a controlling agent, the *central executive*. This is conceived of as a limited capacity supervisory attentional controller, according to Baddeley (1986) very similar to the supervisory attentional system (SAS) proposed by Norman and Shallice (1986) in their model of attentional control. Whereas important progress was made in the investigation of the function and characteristics of the phonological loop (see e.g., Baddeley, 1986, 1997, for reviews), and to a lesser extent in the structure and function of the visuo-spatial sketchpad (see e.g., Logie, 1995), the central executive seemed to resist attempts at clarification. However, one recent attempt at clarification introduced a further fractionation of the working memory system by adding a third slave system, the episodic buffer, which is thought to integrate phonological and visuo-spatial information (see Baddeley, 2000).

In contrast to the situation for the two original slave systems where it proved relatively easy to find tasks calling essentially on the resources provided by these slaves, any task calling on the intervention of the central executive is also bound to call on other subsystems. Nevertheless, a number of tasks were found that can be used in the laboratory to test or to load or to interfere with the central executive. Especially, the family of tasks that call on randomisation appear to be quite useful for the study of executive processes: random number or digit generation, random letter generation (Baddeley, 1966; Brugger, 1997; Evans, 1978; Towse & Neil, 1998; Towse & Valentine, 1997), random keyboard generation (Baddeley, Emslie, Kolodny, & Duncan, 1998), and the generation of random time intervals (De Rammelaere, Stuyven, & Vandierendonck, 1999; Martein, Kemps, & Vandierendonck, 1999; Stuyven & Van der Goten, 1995; Stuyven, Van der Goten, Vandierendonck, Claeys, & Crevits, 2000; Vandierendonck, 2000b, 2000a; Vandierendonck, De Vooght, & Van der Goten, 1998a; Vandierendonck, Kemps, & Fastame, 2000). Consistent with the finding that

speed is an important factor of executive processes in ageing (Bryan & Luszcz, 2000), also tasks based on speeded reactions and speeded choice reactions seem to be useful (Vandierendonck & De Vooght, 1997; Vandierendonck, De Vooght, & Van der Goten, 1998b).

Despite these methodological advances, the concept of central executive seemed to lack clarity so that it proved difficult to formulate and test precise hypotheses about its functioning. In order to cope with these difficulties, a new strategy has been adopted, namely the fractionation of the executive system that in its present form has all the features of a homunculus—a little man in the head controlling all subsidiary cognitive processes (Baddeley, 1996a, 1996b).

In fact, the problems faced by clinical and cognitive neuropsychologists with the ill-defined concept of prefrontal syndrome are similar to those experienced by cognitive psychologists with the notion of central executive. This should not be surprising since the concepts of prefrontal syndrome and central executive are closely related. Moreover, there have been many interactions between cognitive psychology and neuropsychology in as-much that both groups have been exchanging their methodologies, as can be seen in the usage of random generation techniques in neuropsychological research, on the one hand, (e.g., Azouvi, Jokic, Van der Linden, Marlier, et al., 1996; Baddeley, Della Sala, Papagno, & Spinnler, 1997; Beerten, Van der Linden, & Pesenti, 1995; Brown, Soliveri, & Jahanshahi, 1998; Brugger, Monsch, Salmon, & Butters, 1996; Claeys et al., 1999; Hornero, Alonso, Jimeno, Jimeno, & Lopez, 1999; Itagaki, Niwa, Itoh, & Momose, 1995; Jimeno, Jimeno, Alonso, Segovia, & Vargas, 1996; Pollux, Wester, & de Haan, 1995; Spatt & Goldenberg, 1993), and the usage of neuropsychological tests of the prefrontal or dysexecutive syndrome, as it is nowadays more often called in the context of laboratory studies, on the other hand (e.g., Lehto, 1996; Phillips, 1997; Piatt, Fields, Paolo, & Tröster, 1999; Tröster et al., 1998; Gilhooly, Phillips, Wynn, Logie, & Della Sala, 1999; Ward & Allport, 1997; Baddeley, Della Sala, Gray, Papagno, & Spinnler, 1997; Fürst & Hitch, 2000).

In view of these mutual exchanges between neuropsychology and experimental psychology, it is important to pay attention to the potential offered by each new methodology in the study of executive processes. It is in this spirit that the initiative was taken for a special issue on the task switching paradigm and its contribution to the study of executive processes. Although in laboratory research, the dual-task method has been the preferential tool for a long time, its application in the study of executive processes has not been without criticism (see e.g., Allport, 1993; Monsell, 1996). So far, similar criticisms have not been levelled against the task switching paradigm.

Task Switching

Jersild (1927) already showed that under some conditions switching between two simple tasks takes more time than a repetition of the same task. In one of his experiments, participants were required to alternate between the tasks "add 6" and "subtract 3" in response to a list of numbers (alternation condition). They also worked through lists where only one of both tasks was to be performed on each number in the list (repetition condition). The total time to complete the list in the alternation condition was longer than the average time required for completing the lists in the repetition condition. This reaction time difference is known as the *switch cost*. Such a switch cost is only observed, however, if some amount of control is required to perform the switch. The cost associated with a switch between two well-learned S-R associations with no stimulus overlap is small or non-existent. Spector and Biederman (1976), for example, found no cost in switching between adding 3 to a number and naming the opposite of a word. In the latter case, no executive control is required as the tasks can be performed completely stimulus-driven.

The execution of a task requires attention to a particular subset of stimuli in the environment, an intention to respond to these stimuli in a particular way and a procedure to translate the stimuli into appropriate responses. All these components must be tied together into a representation which resists any "temptations" to shift attention, goals or procedures. Without a representation that is stable enough to resist execution of overpracticed habits, intentional behaviour would be impossible. The binding or chaining of all the processes involved in selection and categorisation of the stimulus input, activation of a task goal and a stimulus-response mapping and planning of a motor response is called a task-set (Rogers & Monsell, 1995). Each time a switch between two tasks is required, the previous task-set is no longer valid, and must be inhibited or broken down in some way and a new set must be configured. Rogers and Monsell (1995) refer to these operations as the *reconfiguration of the task-set*. In general, it is agreed that this process of reconfiguration is—at least in part—a controlled process and is an important source of the switch cost. From the literature it is clear that the size of the switch cost decreases as the preparation interval (the time between the cue and the stimulus of the next trial) becomes longer (Allport, Styles, & Hsieh, 1994; Meiran, 1996, 2000; Meiran, Chorev, & Sapir, 2000). In addition, Rogers and Monsell (1995) have shown that the preparation interval calls on controlled processing. They varied the preparation interval and found that with longer intervals the switch cost drops, but this was only the case when the length of the interval was constant in a block of trials; if in a block, intervals of different lengths were presented, length did not affect switch cost. In

those mixed length blocks participants refrained from preparing the next task-set, since they did not know whether it would help them to be ready for the next stimulus.

The alternative hypothesis that the previous task-set decays over the preparation interval was tested by Meiran (1996). He contrasted the controlled preparation and the passive decay explanation in a paradigm in which the upcoming relevant task was cued and he varied the response-cue interval and the cue-stimulus interval independently. During the response-cue interval, no active preparation is possible since the participant does not know whether a switch will be required or not. Once the cue is given, active preparation can start. So, during the response-cue interval only decay is possible, while during the cue-stimulus interval, both passive decay and active preparation can occur. Meiran varied the length of both intervals independently and found that only the length of the cue-stimulus interval affected the switch cost. Together with the findings of Rogers and Monsell (1995) this finding converges on the hypothesis of a controlled preparation process.

There is also evidence, however, that even after a long preparation interval, the switch cost is not completely eliminated. Several authors (e.g., Allport et al., 1994; Meiran, 1996; Meiran et al., 2000; Rogers & Monsell, 1995) have reported the finding that even after a long preparation interval of more than 1 second, a switch cost remains; this is the so-called *residual switch cost*. Especially, the explanation of this residual component of the switch costs remains an issue of debate in today's research programmes. Basically, there are two views. One view posits that a previous task-set must be inhibited to allow a new one to obtain control over behaviour. The stronger the old task-set in comparison to the new one, the stronger the inhibition must be, and consequently, the longer the effects of this inhibition may last. In other words, the residual switch cost in this view is a (passive) side-effect of inhibitory processes required to prevent an old but strong task-set of becoming active. The second view takes the position that an active control process is involved in the residual cost. Specific to this process is that it can only be activated once the stimulus for the next task appears.

The first view was advocated by Allport et al. (1994). They explained the residual switch costs in terms of *task-set inertia*. This is a kind of proactive interference resulting from the previous task-set. More particularly, it is assumed that there is a persisting activation suppression of strong task-sets. When such a suppressed task-set becomes relevant again, it takes longer for this task-set to become dominant. On the basis of this hypothesis they predicted asymmetric switch costs: switching from a task requiring the compilation of a strong set (as in naming the colour of a colour-word printed in a particular colour) would produce larger costs than switching from a weaker or easier task-set (naming the word of a colour-word printed in a particular

colour). Although Allport et al. (1994) presented evidence in favour of this hypothesis in the domain of Stroop interference tasks, Monsell, Yeung, and Azuma (2000) subsequently presented evidence that the asymmetrical dominance relation between task-sets is not predictive of switch costs in general: although the finding reported by Allport et al. (1994) sometimes occurs, (see also e.g., Kavcic, Krar, & Doty, 1999), the opposite outcome may also be observed.

Additional findings motivated Wylie and Allport (2000) to reformulate the task-set inertia hypothesis. They extended the earlier paradigm of (Allport et al., 1994) by comparing blocks of Stroop-type items with blocks of items in which part of the stimulus was neutral, namely colour-neutral stimuli (strings of xxx printed in a particular colour or rectangles of a particular colour) and word-neutral stimuli (colour words printed in black). They found that a residual switch cost was present with all types of stimuli, but the switch cost was much larger in the all-Stroop stimulus blocks. They also showed that after performing a block with all-Stroop stimuli, there was a substantial switch cost in the subsequent colour-neutral block and the size of the switch cost diminished slowly over trials. Similarly, after a block with colour-neutral stimuli, the switch cost in all-Stroop stimuli was initially small, but gradually increased over trials. These findings are clearly consistent with the hypothesis that persisting effects of previously active task-sets affect the size of the switch cost. According to Wylie and Allport (2000) this is best explained in terms of a retrieval hypothesis: on each trial, stimulus-response associations and possibly also goal-related representations are changed, so that the residual switch costs are due to long-term negative priming resulting from the learned S-R associations.

The basic idea that some kind of inhibition is at work was also confirmed by the research of Mayr and Keele (2000). They presented a continuous sequence of simple tasks in which the specific task to be performed was cued before the stimuli were presented. The task could require participants to make a decision about the colour, the orientation, the movement or the size of one of the elementary stimuli in the display. When the cue (e.g., colour) on a particular trial was the same as two trials before, reaction time was reliably longer than when the cue had not been used in the two previous trials. The authors label this effect "backward inhibition", and they showed that the effect is robust and connected to endogenous rather than exogenous control, that it can account for part of the residual switch costs, and that it also occurs in the context of pre-planned task sequences. In addition, they showed that the inhibition effect was present regardless of whether the current target dimension was the same as an irrelevant task dimension on the previous trial and regardless of repetition of the location at which the relevant stimulus was shown. In other words, the so-called backward inhibition was present

irrespective of the opportunities for negative priming.

This set of findings fits in nicely with the second view that some form of active or endogenous control is at the basis of the residual switch costs. Rogers and Monsell (1995) were the first to advocate such an explanation. They introduced the alternating runs paradigm in which the participant was required every second trial to switch between two tasks. They showed that a (residual) switch cost was present only on the switch trial. Even when the participants switched every four trials, only the first trial in the sequence of four was delayed due to switch costs. In the view of the authors, part of the task-set reconfiguration is triggered by the stimulus shown on the switch trial. Yet, the interpretation as well as the finding contrast with an observation by Mayr and Kliegl (2000) that when the task is difficult, a small cost is still present on the second trial after the switch.

Rubinstein, Meyer, and Evans (in press) compared performance in alternating task and single-task lists and varied the complexity of the tasks and the presence of a cue. Besides a general dual-task (alternating list) cost, they found that the reaction time switch cost increased with task complexity and decreased when a cue was present. These two effects were additive and point to separate and independent effects related to goal shifting and rule activation. These two control processes are thought by these authors to represent two stages of control.

Working within a rather similar framework, Vandierendonck and Caessens (2000) used the alternating runs paradigm with two independent tasks in close temporal succession (SOA of 700 ms) in each trial. Although the stimulus-response rules for each of the two tasks in the trial were independent, the tasks shared the goals of attending to a particular symbol within the stimulus display. With each task switch, the common goal and the relevant response rules had to be shifted. Therefore a larger switch cost was predicted for the first task within each trial (shift of goal and rules) than for the second task (shift rules only). Over a series of experiments in which the amount and the location of cueing and the frequency of shifting were varied, this prediction was confirmed.

In summary, it may be said that so far there is evidence both for the operation of non-executive as well as executive control processes in the production of residual switch costs. In view of the findings thus far, the crucial question does not seem to be whether the residual costs are due to controlled processing but rather which kind of mechanism can explain the effects observed.

Task Switching, Ageing and Neuropsychology

If it is true that the switching costs are due to executive processes and that with ageing, the efficiency of these processes suffers, it is expected that switch costs become larger with age. In clinical settings, the Trail Making Test (TMT, Reitan, 1958) is often used to study task switching behaviour. The test consists of two pages with randomly placed circles. On the first page, the circles contain numbers and the participants are asked to connect the circles in the correct order (1-2-...). On the second page, the circles contain numbers and letters and the participants have to connect both sequences alternately (1-A-2-B-...). Obviously, completion of the second page requires the participant to alternate (switch) between two task-sets, namely locating the next digit and locating the next letter.

Because usage of the TMT to study switch costs raises more problems than it solves, Salthouse et al. (2000) developed a better standardised version of the TMT, named the Connections Test. They employed it to investigate switch costs as a function of ageing. When partialing out perceptual speed, they found no adverse effects on switch costs associated with normal ageing. A similar result was reported by Wecker, Kramer, Wisniewski, Delis, and Kaplan (2000) on the basis of the California Trail Making Test.

Studies investigating task switching in specific neurological populations have been rare (but see also Van der Linden, Meulemans, Marczewski, & Collette, 2000). The study by Meiran, Levine, Meiran, and Henik (2000) is an interesting exception. These investigators studied task switching in Schizophrenic patients. Large switching costs were observed. Although it is tempting to attribute these costs to defective control processes, it is probable that they mainly reflect poor memory for information about the task context including the response rules.

Brain imaging studies of task switching have been equally exceptional. One study found the involvement of the prefrontal cortex in addition to a series of other areas (Dove, Pollmann, Schubert, Wiggins, & von Cramon, 2000). Because few procedural details of this study are available and because an extremely simple task set-up was used, it is difficult to link this finding to the other work on task switching.

Further Work

This brief and necessarily incomplete review shows that in a short period of time a lot of new work has been published on the issue of task switching. The picture evolving from this work is at best fragmented but it contains already a few interesting lines that give indications as to how one can pro-

ceed from here.

Foremost, what needs to be clarified concerns the notion of task-set. After all, the notion is pretty vague, and as long as it is not made clear what constitutes a task-set, which processes are involved, much of the discussion about the involvement of executive control processes remains speculative. Moreover, when is a process a control process or an executive process? Which criteria need to be fulfilled for an executive control process to occur. Many researchers tend to identify executive control with additional processes being executed for the purpose of control. However, executive control might also be conceived of as an inhibitory process that is automatically set in motion once particular preconditions are met (see also Mayr & Keele, 2000). With the further assumption that these inhibitory processes take time or delay re-activation of the inhibited task-set, a major part of the time costs observed in task switching and in other executive task paradigms can be explained.

If it appears to be true that maintenance of information in working memory is involved in tasks requiring executive control, then a number of new—or better, old—questions remain to be solved. What does it mean to store information in working memory? Is working memory to be conceived as a separate store to which information is transferred to be maintained there for some time or can we simply think of working memory as a temporarily active state of information stored in a permanent memory system. This is really an old question, but as shown in the confrontation of different theories of working memory by Miyake and Shah (1999) it is still a central one and a vivid one, and for a number of reasons which cannot be elaborated here, the answer is not a simple yes or no. Related to this issue is the question which operations are involved in retrieval of information from permanent memory, which operations are involved in activation and deactivation or inhibition of representations. Are these operations control processes initiated by an “intentional” act or do these processes operate relatively automatically given particular preconditions are met.

Anyway, it should also be clear that the central executive is probably not a unitary system as a distinction between executive functions is possible. On the basis of an individual differences analysis, Miyake et al. (2000) have shown that a distinction between three executive functions (task shifting, inhibition and updating) was possible, although the three functions were not completely independent. However, the finding that performance on some neuropsychological tasks, such as the Wisconsin Card Sorting Test, the Tower of Hanoi and random number generation could be explained on the basis of these functions, while this could not be achieved for dual-task performance, raises the question whether the complete set of executive functions is homogeneous at all.

All these questions show that the task switching paradigm may be considered as another tool to be included in our experimental toolbox, but that it in itself cannot solve the many questions that have been around for many years. Nevertheless, it is a tool and if used properly and in combination with the many other tools available, it may help to clarify the important issues.

A Special Issue?

Precisely these considerations about the current state of the art lay at the basis of the initiative to collect a number of papers in a special issue devoted to the theme of task switching and its place in present day research. Although some of the research questions addressed within this theme were covered in the present article, many new lines of research on task switching are being developed. The central purpose of this special issue was to give a rather broad overview of the developments within this domain.

One of the very attractive ideas with respect to action control and the related issues of repetition and alternation (switching) effects finds its origins in the hypothesis that features of perception and action are represented at least in part with the help of common codes (see e.g., Prinz, 1997). Reasoning further along these lines Hommel (1996) proposed the action concept theory which assumes that every action has a perceptual effect and that the codes used to represent this effect are shared with the codes used to represent stimuli. An important implication of this viewpoint is that during the preparation of a particular response one is blind for the features a stimulus shares with that response (Müsseler & Hommel, 1997). Furthermore, in a paradigm with two S-R tasks overlapping in time, the theory predicts a backward compatibility effect that has been confirmed in a number of contexts (Hommel, 1998a; Hommel & Eglau, 1999; Van der Goten, 1999; Van der Goten, Lammertyn, De Vooght, & Hommel, *in press*). Another recent extension concerns the issue of binding stimuli and responses into so-called event files (Hommel, 1998b). Such a binding realises an integration of events essentially providing a context for actions. The article by Hommel, Pösse, and Waszak (2000) elaborates this theme in relation to task switching, and presents an overview of their findings.

Another way of looking at task intentions and their configuration or reconfiguration is by studying the task space. When a person has to switch between two tasks this implies that the task stimuli may change or not, that attention to the stimuli or their components may change, that the responses or their features may change and that the overall intention may change (see e.g., Kleinsorge & Heuer, 1999). If all the possible variations are taken into account it is possible to describe the complete task space as a context in

which switches and repetitions of task-sets are performed. This is precisely the angle taken by Kleinsorge (2000) in this issue and it allows to estimate the relative importance of the component changes and it gives clues about the cognitive organisation of all these components.

To answer the questions raised by the task switching paradigm it does not suffice to look at behaviour patterns of young and healthy persons. As was already evident in the overview presented in the current article, a comparison of performance of healthy young and old-age persons may reveal the extent to which task switching calls on executive control. If it can be shown that executive processes play a role at all in ageing, it may also be possible to localise more precisely the components responsible for this. The article by van Asselen and Ridderinkhof (2000) fits in with this line of questioning. Interestingly, and contrary to the findings of Salthouse et al. (2000) and Wecker et al. (2000), they found specific ageing affects demonstrating the involvement of executive control.

Executive controlled processing can also be studied in a neuropsychological context, for example by means of an experimental methodology or by means of brain imaging techniques in healthy people and neuropsychological patients. Van der Linden et al. (2000) present an impressive overview of findings based on those approaches. By doing so, they put the issue of task-switching in a much broader context of executive control and this forms a nice way to close this special issue. There are of course many more approaches that can be followed or viewpoints that can be taken to extend our knowledge about the processes involved in task switching. However, the present selection of papers should provide the interested reader with some appetite for this theme. I also hope that the articles collected in the present issue help to point out how the paradigm can contribute in these efforts.

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