Task switching

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Everyday life requires frequent shifts between cognitive tasks. Research reviewed in this article probes the control processes that reconfigure mental resources for a change of task by requiring subjects to switch frequently among a small set of simple tasks. Subjects' responses are substantially slower and, usually, more error-prone immediately after a task switch. This 'switch cost' is reduced, but not eliminated, by an opportunity for preparation. It seems to result from both transient and long-term carry-over of 'task-set' activation and inhibition as well as time consumed by task-set reconfiguration processes. Neuroimaging studies of task switching have revealed extra activation in numerous brain regions when subjects prepare to change tasks and when they perform a changed task, but we cannot yet separate 'controlling' from 'controlled' regions.

A professor sits at a computer, attempting to write a paper. The phone rings, he answers. It's an administrator, demanding a completed 'module review form'. The professor sighs, thinks for a moment, scans the desk for the form, locates it, picks it up and walks down the hall to the administrator's office, exchanging greetings with a colleague on the way. Each cognitive task in this quotidian sequence – sentence-composing, phone-answering, conversation, episodic retrieval, visual search, reaching and grasping, navigation, social exchange – requires an appropriate configuration of mental resources, a procedural 'schema' [1] or 'task-set' [2]. The task performed at each point is triggered partly by external stimuli (the phone's ring and the located form). But each stimulus affords alternative tasks: the form could also be thrown in the bin or made into a paper plane. We exercise intentional 'executive' control to select and implement the task-set, or the combination of task-sets, that are appropriate to our dominant goals [3], resisting temptations to satisfy other goals.

Goals and tasks can be described at multiple grains or levels of abstraction [4]: the same action can be described as both 'putting a piece of toast in one's mouth' and 'maintaining an adequate supply of nutrients'. I focus here on the relatively microscopic level, at which a 'task' consists of producing an appropriate action (e.g. conveying to mouth) in response to a stimulus (e.g. toast in a particular context). One question is: how are appropriate task-sets selected and implemented? Another is: to what extent can we enable a changed task-set in advance of the relevant stimulus – as suggested by the term 'set'? Introspection indicates that we can, for example, set ourselves appropriately to name a pictured object aloud without knowing what object we are about to see. When an object then appears, it is identified, its name is retrieved and speech emerges without a further 'act of intention': the sequence of processes unfolds as a 'prepared reflex' [5,6].

Many task-sets, which were initially acquired through instruction or trial and error, are stored in our memories. The more we practice a task, or the more recently we have practised it, the easier it becomes to re-enable that task-set. At the same time, in the absence of any particular intention, stimuli we happen to encounter evoke tendencies to perform tasks that are habitually associated with them: we unintentionally read the text on cereal packages or retrieve the names of people we pass in the street. More inconveniently, stimuli evoke the tendency to perform tasks habitually associated with them despite a contrary intention. The standard laboratory example of this is the Stroop effect [7]: we have difficulty suppressing the reading of a colour name when required to name the conflicting colour in which it is printed (e.g. 'RED' printed in blue). Brain damage can exacerbate the problem, as in 'utilization behaviour', which is a tendency of some patients with frontal-lobe damage to perform the actions afforded by everyday instruments, such as matches, scissors and handles, even when these actions are contextually inappropriate [8].

Hence the cognitive task we perform at each moment, and the efficacy with which we perform it, results from a complex interplay of deliberate intentions that are governed by goals ('endogenous' control) and the availability, frequency and recency of the alternative tasks afforded by the stimulus and its context ('exogenous' influences). Effective cognition requires a delicate, 'just-enough' calibration of endogenous control [9] that is sufficient to protect an ongoing task from disruption (e.g. not looking up at every movement in the visual field), but does not compromise the flexibility that allows the rapid execution of other tasks when appropriate (e.g. when the moving object is a sabre-toothed tiger).

To investigate processes that reconfigure task-set, we need to induce experimental subjects to switch between tasks and examine the behavioural and brain correlates of changing task. Task-switching experiments are not new (Box 1), but the past decade has seen a surge of interest, stimulated by the development of some novel techniques for inducing task switches and getting subjects to prepare for them (Box 2), and some surprising phenomena revealed thereby, as well as by the broader growth of interest in control of cognition (e.g. [10]).

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Box 1. Early research on task-set and task switching

The intentional and contextual control of 'set' ('Einstellung') was discussed in 19th and early 20th century German experimental psychology. In 1895, von Kries used as examples the way the clef sign changes the action performed to play a note on the musical stave, and the way the current state of a game changes how one sets oneself to respond to an opponent's behaviour [58]. Exner and the Wurzburg school described the 'prepared reflex', and, in 1910, Ach described experiments on overlearned responses competing with the acquisition of a novel stimulus–response mapping, see [6]. Until recently, in the English-language literature, ideas about control of task-set have been stimulated mainly by the observation of impairments of control, both in everyday action and as a result of neurological damage, see [2], despite some experimentation on normal executive function in cognitive laboratories [5].

The invention of the task-switching paradigm is credited to Jersild [59] who had students time themselves working through a list of items, either repeating one task or alternating between two. Some task pairs (adding 3 to vs. subtracting 3 from numbers) resulted in dramatic alternation costs; others (adding 3 to a number vs. writing the antonym of an adjective) did not. Jersild's paradigm was revived, and his results replicated using discrete reaction-time measurements, by Biederman and Spector [60]. Despite this work and some pioneering task-cueing studies (e.g. [61–63]) it was only in the mid 1990s that the present surge of research on task switching developed.

Task switching: basic phenomena

In a task-switching experiment, subjects are first pre-trained on two or more simple tasks afforded by a set of stimuli (Figs 1 and 2 provide examples). Each task requires attention to, and classification of, a different element or attribute of the stimulus, or retrieval from memory or computation of a different property of the stimulus. Then, a stimulus is presented on each of a series of trials and the subject performs one of the tasks. There are several methods for telling the subject which task to perform (Box 2), but in all cases the task sometimes changes from one trial to the next, and sometimes does not. Thus, we can examine performance or brain activation on and following trials when the task changes for evidence of extra processing demands that are associated with the need to reconfigure task-set. We can also examine the effects of localized brain damage, transient magnetic stimulation (TMS) or pharmacological interventions on behavioural indices of switching efficiency. Four phenomena of primary interest (of which the first three are illustrated in Figs 1 and 2) are described below.

Switch cost (task-repetition benefit)

Generally, responses take longer to initiate on a 'switch trial' than on a 'non-switch' or task-repetition trial, often by a substantial amount (e.g. 200 ms relative to a baseline of 500 ms). Also, the error rate is often higher after a task switch.

Preparation effect

If advance knowledge is given of the upcoming task and time allowed to prepare for it, the average switch cost is usually reduced.

Residual cost

Preparation generally does not eliminate the switch cost. In the examples shown, the reduction in switch cost seems to have reached a substantial asymptote, the 'residual cost', after ~600 ms of preparation. Substantial residual costs have been reported even when 5 s or more is allowed for preparation (e.g. [11,12]).

Mixing cost

Although performance recovers rapidly after a switch (Fig. 1), responses remain slower than when just one task must be performed throughout the block: there is a long-term as well as a transient cost of task switching.

These phenomena have been demonstrated with a wide range of different tasks and they are modulated by numerous other variables. What explains them?

Sources of the switch cost

Time taken by control operations

To change tasks, some process or processes of 'task-set reconfiguration' (TSR) – a sort of mental 'gear changing' – must happen before appropriate task-specific processes can proceed. TSR can include shifting attention between stimulus attributes or elements, or between conceptual criteria, retrieving goal states (what to do) and condition–action rules (how to do it) into procedural working memory (or deleting them), enabling a different response set and adjusting response criteria. TSR may well involve inhibition of elements of the prior task-set as well as activation of the required task-set.

An account of the switch cost that appeals intuitively is that it reflects the time consumed by TSR. The preparation effect then suggests that, if sufficient time is allowed, TSR can, to some extent, be accomplished under endogenous control, before the stimulus onset. The residual cost is more perplexing. Rogers and Monsell [13] suggest that

Box 2. Task switching paradigms

There are several methods of telling a subject which task to do on each trial. **Jersild's method** (Box 1), which is still sometimes used (e.g. [39]), compares the duration of blocks of trial in which the subject alternates tasks as rapidly as possible with blocks in which they repeat just one task. This contrast of alternated and repeated tasks can also be used with discrete reaction-time measurement (e.g. [14]). However, this comparison confounds switch costs and mixing costs. Also, the alternation blocks impose a greater working memory load – to keep track of the task sequence and maintain two tasks in a state of readiness – and might promote greater effort and arousal. These problems are avoided by the **alternating-runs paradigm** [13], in which the task alternates every *N* trials, where *N* is constant and predictable (e.g. Fig. 1, predictable condition, and Fig. 2), so that one can compare task-switch and task-repetition trials within a block. An alternative is to give the subjects short sequences of trials [20,27] with a **prespecified task sequence** (e.g. colour–shape–colour). Either way, one can manipulate the available preparation time by varying the stimulus–response interval, but this also varies the time available for any passive dissipation of the previous task-set.

In the **task-cueing paradigm** [63,64], the task is unpredictable, and a task cue appears either with or before the stimulus (e.g. Fig. 1, random condition). It is now possible to manipulate independently the cue–stimulus interval (allowing active preparation) and the response–cue interval (allowing passive dissipation). Alternatively, in the **intermittent-instruction paradigm**, the series of trials is interrupted occasionally by an instruction that indicates which task to perform on the trials following the instruction [65]. Even when the instruction specifies continuing with the same task, there is a 'restart' cost after the instruction [29], but this is larger when the task changes; the difference yields a measure of switch cost.

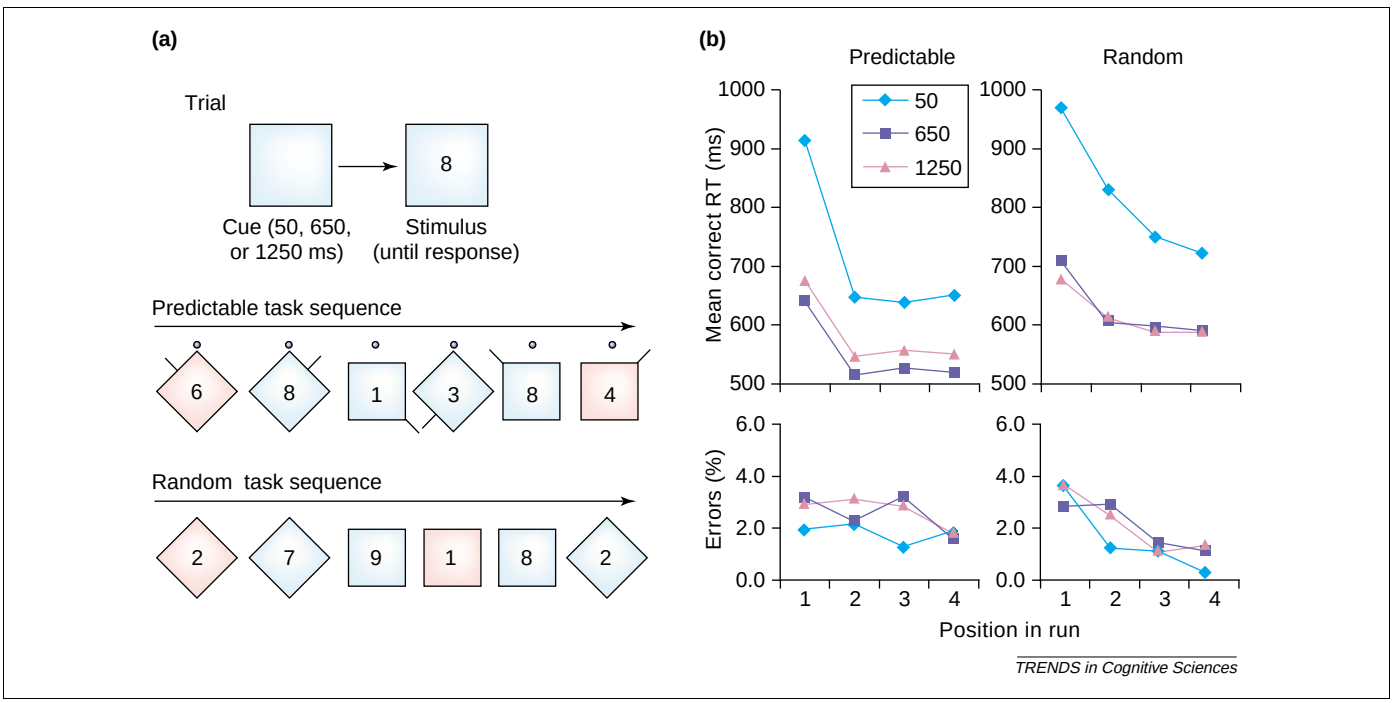

Fig. 1. Predictable and unpredictable task switching. In this experiment (Ref. [42], Exp. 2), the tasks were to classify the digit as either odd/even or high/low, with a left or right key-press. (a) For some subjects, the task was cued by the background colour (as illustrated) and for others by the background shape; the colour or shape changed at the beginning of every trial. The response–stimulus interval in different blocks was 50 ms, 650 ms and 1250 ms, during which subjects could prepare for the next stimulus. In some blocks, the task changed predictably every four trials (with a 'clock hand' rotating to help keep track of the sequence): the 'switch cost' was limited to the first trial of the changed task (b). In other blocks, the task varied randomly from trial to trial and recovery from a task switch was more gradual. In both cases, the switch cost was reduced by ~50% by extending the time available for preparation to 650 ms (the 'preparation effect'); a further increase had little effect (the 'residual cost'). These data demonstrate that, at least in normal, young adults, even with complete foreknowledge about the task sequence, switch costs are large, and that recovery from a task switch is characteristically complete after one trial. When the task is unpredictable, recovery might be more gradual, but a few repetitions of a task results in asymptotic readiness for it. (Data redrawn with permission from Ref. [42].)

part of TSR cannot be done until exogenously triggered by stimulus attributes that are associated with the task; Rubinstein *et al.* [14] characterize this part as retrieval of stimulus–response rules into working memory. An alternative account, from De Jong [15], makes no distinction between endogenous and exogenously-triggered TSR. It proposes that, although subjects attempt TSR before stimulus onset (given the opportunity), they succeed on only a proportion of switch trials. If they succeed they are as ready for the changed task as on a task-repetition trial. If they 'fail to engage', the whole TSR process must be performed after stimulus onset. This idea of TSR as a probabilistic all-or-none state change is supported by the fit of a discrete-state mixture model to the distribution of reaction times (RTs) on prepared switch trials [15,16]. But why should TSR be all-or-none? One rationale is that TSR includes an attempt to retrieve either the goal or the task rules from memory; retrieval attempts either succeed or fail [17,18].

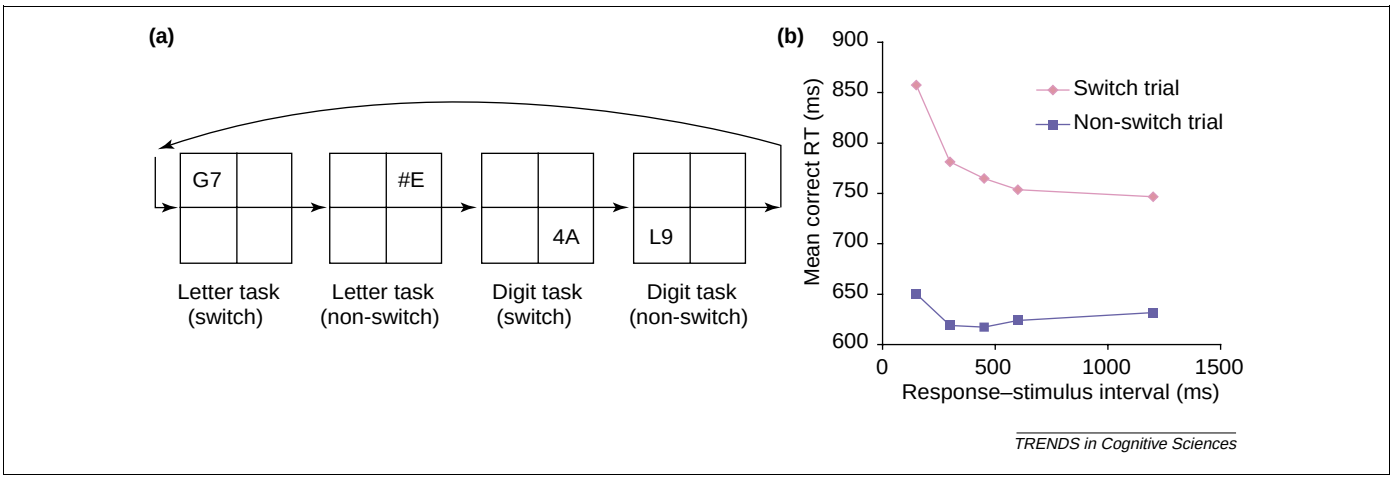

Fig. 2. Preparation effect and residual cost. (a) In this experiment (Ref. [13], Exp. 3), the stimulus is a character pair that contains a digit and/or a letter. The tasks were to classify the digit as odd/even, or the letter as consonant/vowel. The task changed predictably every two trials and was also cued consistently by location on the screen (rotated between subjects). (b) The time available for preparation (response–stimulus interval) varied between blocks. Increasing it to ~600 ms reduced switch cost (the 'preparation effect'), but compared with non-switch trials there was little benefit of any further increase, which illustrates the 'residual cost' of switching. (Data redrawn with permission from Ref. [13].)

Transient task-set inertia

Consider Stroop stimuli. It is well-known that incongruence between the colour in which the word is displayed and the colour it names interferes much more with naming the display colour than with naming the word, an asymmetry of interference that is attributable to word naming being the more practised, and hence 'stronger', task-set [19]. Surprisingly, if subjects must switch between this pair of tasks, switching to the stronger task results in the larger switch cost [20–22]. In another striking example, bilingual subjects named digits more slowly in their second language on non-switch trials, but on switch trials named more slowly in their first language [23]. This surprising asymmetry of switch costs eludes explanation in terms of the duration of TSR. How could it take longer to reconfigure for the more familiar task? Allport *et al.* [20] propose that one must apply extra inhibition to the stronger task-set to enable performance of the weaker. This inhibition then carries over to the next trial; overcoming the inhibition prolongs response selection.

Subsequent work reveals some problems with this account. For example, the surprising asymmetry of switch costs can be reversed by manipulations that produce only a modest reduction in the asymmetry of Stroop-like interference between the tasks [22,24]. However, this pattern can be accommodated by a model that combines transient persistence of task-set activation (or inhibition) with the assumption that executive processes apply the minimum endogenous-control input that enables the appropriate task, given the anticipated interference [22]. The detection of cross-task interference during a trial might also prompt the ramping-up of endogenous control input, which would lead to greater TSI on a switch trial following an incongruent stimulus [9].

Other observations support the transient carry-over of task-set activation from trial to trial. Several researchers [25,26] report evidence that, with preparation held constant, a longer delay after the last performance of the previous task improves performance on the switch trial. This suggests dissipating activation of the competing task-set. Sohn and Anderson [18] fit data on the interaction between preparation interval and foreknowledge with a model that assumes exponential decay of task-set activation following a trial, and an endogenous preparation process whose probability of success increases throughout the preparation interval. There is also evidence for persistence of inhibition applied to a task-set in order to disengage from it: so, for example, responses are slower on the last trial of the sequence Task A, Task B, Task A, than the sequence Task C, Task B, Task A [27,28].

Associative retrieval

Even when performing only one task (e.g. word naming), responses are slower if subjects have performed another task afforded by the same stimuli (e.g. colour naming) in the previous few minutes [20,21,29]. This long-term priming has been attributed to associative retrieval of task-sets that are associated with the current stimulus [29,30], and seems likely to be the source of the mixing cost. Allport and colleagues found this priming to be magnified on a switch trial or when performance was merely resumed after a brief pause, which suggests that associative interference may contribute also to switch costs [21,29]. Further experiments [30] demonstrated that this priming can be quite stimulus-specific. In these experiments, each stimulus was a line drawing of one object with the name of another superimposed (e.g. a lion with the word APPLE). In the first block, subjects named the object, ignoring the word. Later, they showed larger switch costs for naming the word in stimuli for which they had previously named the picture, even if only once and several minutes before.

All of the above?

Initial theorising tended to try to explain switch costs in terms of just one mechanism (e.g. [13,20]). Although single-factor models of task switching continue to be proposed [31] most authors now acknowledge a plurality of causes, while continuing to argue over the exact blend. For example, although long-term effects of task priming imply associative activation of competing task-sets by the stimulus, the contribution this makes to the transient switch cost observed with small sets of stimuli, all recently experienced in both tasks, is uncertain. Moreover, residual switch costs occur even with 'univalent' stimuli (i.e. those associated with only one task) for which there should be no associative competition [13,26], and switch costs sometimes do not occur for bivalent stimuli where there should be massive associative competition, such as switching between prosaccades and antisaccades to peripheral targets [32]. Transient carry-over of task-set activation or inhibition is now well established as an important contributor to switch costs, especially the residual cost, but it remains unclear whether the effect is to slow task-specific processes (e.g. response selection) or to trigger extra control processes (ramping up of control input when response conflict is detected). A combination of both mechanisms is likely. Something of a consensus has developed around the idea that the preparation effect, at least, reflects a time-consuming, endogenous, task-set-reconfiguration process, which, if not carried out before the stimulus onset, must be done after it.

Issues for further research

Unfortunately, the foregoing consensual account of the preparation effect is not without problems. First, there are studies in which the opportunity for preparation with either full [33] or partial [34] foreknowledge of the upcoming task does not reduce the switch cost, even though it improves overall performance. Second, in task-switching experiments, to know whether TSR is necessary, a subject must discriminate and interpret an external cue (with unpredictable switching), retrieve the identity of the next task from memory (with predictable switching), or both (many predictable switching experiments provide external cues as well). The contribution of these processes to switch costs has been neglected. Koch [35] has reported that, with predictable switching, a preparation interval reduces the switch cost only when there is an external cue to help subjects remember which task is next. Logan and Bundesen [36] found that changing the cue when repeating the task produced nearly as much of a preparation

effect as changing both cue and task. Hence, processes of interpreting the cue and/or determining whether TSR is required might contribute much of the preparation effect. It is even possible that, in some cases, these processes are so demanding that they constitute a separate task, thus vitiating the distinction between 'switch' and 'non-switch' trials.

Another intriguing issue is the role of language. Introspection indicates that in both everyday life and task-switching experiments people to some extent verbalize what they intend to do next ('*er…colour*') and how ('*if red, this key*'). Goschke [9] found that requiring subjects to say an irrelevant word during a 1.5 s preparation interval abolished the reduction in switch cost observed when the subject either named the task ('*colour*' and '*letter*') or said nothing. He attributed this to interference with verbal self-instruction, extending to TSR the Vygotskian view [37] that self-instruction using language is fundamental to self-regulation. Others have found that irrelevant concurrent articulation (e.g. saying '*one–two–one–two…*') – which is known to interfere with phonological working memory – impairs performance disproportionately in task alternation compared to single task blocks [38,39]. It is also suggested that the association claimed between damage to the left prefrontal cortex and switching deficits (see below) reflects impaired verbal mediation caused by left hemisphere damage, rather than a more general control deficit [40]. However, subjects in these studies were relatively unpractised. Traditional theories of skill acquisition [41] assign language a relatively transitory role in task-set learning. A task-set, especially if acquired via the verbal instructions of another person, may be represented initially via verbal self-instruction, but after sufficient practice, control shifts from declarative (including verbal) representations to a learned, procedural representation. Standard examples are learning to shift gear or tie a knot. Hence, we might expect that any cost or benefit of verbal self-instruction in reconfiguring a task-set would vanish with practice.

Experiments on task switching have thrown up numerous other puzzling observations. Why does an opportunity for preparation often reduce switch costs without reducing Stroop-like interference from the other task [13,25,42]? Why are switch costs larger when the response is the same as the previous trial [13]? We are unlikely to make sense of the increasingly complex set of variables that are known to influence switch costs without either computational simulation [43,44] or mathematical modelling [18,22,45,46] of their interactions. Progress in disentangling the complex causation of switch costs is necessary to interpret the effects of ageing [47–49] and brain damage [50,51] on, and individual differences [52] in, task-switching costs, and their association and dissociation with behavioural indices of other control functions. Even without a full understanding of their causation, the substantial magnitude of switch costs should also be an important consideration in the design of human–machine interfaces that require operators to monitor multiple information sources and switch between different activities under time pressure, such as in air-traffic control.

Brain correlates of task switching

At first glance, task switching lends itself well to the subtractive methodology of neuroimaging and electrophysiology. We can compare event-related activation in trials that differ only in whether they do or do not follow another of the same task. Numerous brain regions, usually in medial and lateral regions of the prefrontal cortex, but sometime in parietal lobes, cerebellum and other subcortical regions, are reported to be more active on switch than on non-switch trials. As one example, left dorsolateral prefrontal cortex has been reported to be more active when subjects switch the attribute attended to [53,54], and this appears consistent with evidence that patients with left frontal damage have behavioural abnormalities in switching between attributes [50,51].

Regrettably, as we have learned from behavioural studies, task switch and repeat trials are likely to differ in ways other than the occurrence of TSR. There may be extra interference at the levels of both task-set and stimulus–response mapping. The greater difficulty of switch trials is likely to elicit general arousal and extra error-monitoring. Moreover, even if region X contains an executive 'module' that reconfigures the behaviour of regions A, B and C, we would expect to see differential activation, not only of the controlling region X, but also of areas A, B and C, much as we see modulation of activation in striate and extrastriate cortex when visual attention is shifted endogenously [55]. Differential activation evoked by stimuli on switch and repeat trials does not differentiate between the 'source' and the 'target' of the control.

One approach is to try to isolate the brain activity that is associated with preparing for a task switch. By stretching out the preparation interval to 5 s [11], 8 s [12] and 12.5 s [54], one can try to separate modulations of the blood-oxygen-level-dependent (BOLD) signal that are linked to preparatory activity from changes associated with processing of the stimulus on switch trials. Some have reported that preparation for a switch evokes extra activation in regions that are different from those that undergo extra activation to a switch-trial stimulus [11,54] whereas others have not [12]. However, long preparation intervals might either require extra processing to maintain preparation, or encourage subjects to postpone preparation. To deal with this, Brass and von Cramon [56] compared activation in trials with a task cue followed by a stimulus 1.2 s later, trials in which the stimulus was omitted, trials in which the cue was delayed until the stimulus onset, and null trials. Cue-only trials caused activation in the left inferior frontal junction and the pre-SMA region that correlated with the behavioural cueing benefit in cue-stimulus trials. When the cue was delayed, this activation was also delayed. Hence this activity seems to be cue-related, but it is unclear (as in behavioural studies) whether it is associated with interpreting the cue or the consequent TSR.

In a study focusing on the medial frontal cortex, Rushworth *et al.* [57] interrupted a series of stimuli every 9–11 trials with a 'stay/shift' cue. When the cue indicated whether to maintain or reverse the left/right response rule in the following trials, a larger BOLD signal was evoked in the pre-SMA region by 'shift' than by 'stay'

cues. When the cue specified whether to maintain or switch the stimulus dimension (colour versus shape) used to direct attention for a perceptual detection task, a more posterior 'hot-spot' was seen. To determine whether these activations were functionally essential, brief trains of TMS pulses were applied to these regions. TMS following a shift, but not a stay, cue substantially prolonged RT to the upcoming stimulus, but only for the response-rule reversal. Hence activity in the pre-SMA region is, apparently, needed to reverse a stimulus–response assignment. We do not know whether this activity reflects the source or the target of an 'act of control', or both.

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