Exp Brain Res (2002) 144:528–537
DOI 10.1007/s00221-002-1075-z

RESEARCH ARTICLE

Mariya V. Cherkasova · Dara S. Manoach
James M. Intriligator · Jason J.S. Barton

Antisaccades and task-switching: interactions in controlled processing

Received: 3 October 2001 / Accepted: 12 February 2002 / Published online: 17 April 2002

Abstract Smaller latency costs for switching from dominant (habitual) to non-dominant (unusual) tasks compared to the reverse direction have been noted in some studies of task-switching. This asymmetry has been cited as evidence of inhibitory effects from the prior trial. We examined accuracy and latency costs of task-switching between prosaccades and antisaccades, where task-switching is limited to stimulus-response re-mapping and occurs between tasks highly asymmetric in dominance. Eighteen subjects executed prosaccades and antisaccades in single-task and mixed-task blocks. In mixed-task blocks, antisaccade and prosaccade trials were ordered randomly, resulting in 'repeated' trials that were preceded by the same type of trial (i.e. antisaccade-antisaccade), and 'switched' trials that were preceded by the opposite type of trial. Comparisons of the single-task blocks and repeated trials of the mixed-task blocks indexed the mixed-list costs, which were small for prosaccades and insignificant for antisaccades. Comparison of the repeated and switched trials from the mixed-task blocks indexed the residual task-switch cost. Accuracy costs of task-switching and antisaccades were equivalent. The accuracy of trials incorporating both switching and antisaccades in a single response (i.e. switched antisaccade) equalled the product of the accuracies of doing each operation alone, supporting independence of these two functions. In contrast, the latency cost of antisaccade performance was 3 times greater than that of task-switching. Task-switching from prosaccades to antisaccades resulted in a paradoxical decrease in antisaccade latency. This decrease correlated with other indices of vigilance, with the paradoxical effect minimized in more attentive observers. The latency data suggest that either an antisaccade on the prior trial perturbs saccadic responses more than a task-switch, or concurrent task-switching specifically facilitates antisaccades. In either case, the paradoxical benefit of task-switching for antisaccades challenges current models of task-switching.

Keywords Antisaccades · Task-switch · Executive · Attention · Latency

Introduction

The ability to perform volitional acts rather than reflexive responses to stimuli is an important component of daily human activity. Volitional control processes have been variously labeled as 'intention', 'executive functions', 'the Will', the 'supervisory attentional system', and 'anterior attentional functions'. These are internal processes that control behavioural responses to external stimuli, conceived by some as 'task demand units' that modulate stimulus-driven processing (Cohen et al. 1990). It has been suggested that executive function is not one but several component processes, each with a distinct anatomical substrate in the frontal lobe (Stuss et al. 1995). A few of these proposed functional components are suppression of reflexive responses, switching of response mode, and performance of novel actions. Engaging executive components places demands on cognitive processes; the 'costs' of executive control are usually measured as differences in error rate and response latency.

Some responses are overlearned, habitual, and reflex-like; others are rare and sometimes novel to a participant. Any two possible responses to a stimulus may differ in the participant's pre-experimental experience, intra-experimental practice, or stimulus-response compatibility (Monsell et al. 2000). The degree of asymme-

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M.V. Cherkasova · D.S. Manoach · J.M. Intriligator
J.J.S. Barton (✉)
Department of Neurology, KS452,
Beth Israel Deaconess Medical Center, Harvard Medical School,
330 Brookline Avenue, Boston, MA 02215, USA
e-mail: jbarton@caregroup.harvard.edu
Tel.: +1-617-6671243, Fax: +1-617-9755322

J.J.S. Barton
Department of Ophthalmology,
Beth Israel Deaconess Medical Center, Harvard Medical School,
Boston, MA 02215, USA

J.J.S. Barton
Department of Bioengineering, Boston University, Boston, MA,
USA

try in these factors between any two responses can vary greatly, along a ‘dominant/non-dominant’ spectrum (Cohen et al. 1990). An habitual or practised association of a stimulus with a particular response renders that response dominant over a less practiced one. The Stroop task is an extensively studied example. It presents subjects with a word naming a colour (e.g. red), printed in ink of a different colour (e.g. blue). Reading the colour name is dominant over stating the ink colour (Cohen et al. 1990; Stroop 1935).

Another, perhaps more extreme example of a dominant/non-dominant response pairing is the antisaccade task. The habitual response to items of interest in the peripheral visual field – particularly suddenly appearing objects – is to shift gaze to them with a ‘prosaccade’. Humans make prosaccades virtually every waking second. However, if requested, one can make a saccade in the direction opposite to that of a target – an antisaccade (Hallett 1978). Almost no participants have pre-experimental experience with antisaccades. Due to this asymmetry in dominance, antisaccades require a much higher degree of voluntary control than do prosaccades, which is evidenced by their directional accuracy and response latency costs (Roberts et al. 1994). Even when under certain demanding experimental conditions prosaccades are known to require some voluntary control, interference effects show that the degree of control still remains greater for antisaccades in these settings (Stuyven et al. 2000).

Task- or response-switching is another type of ‘anterior attentional function’ (Stuss et al. 1995). Studies of task-switching consistently find that latencies are longer and error rates higher on ‘switched’ than on ‘repeated’ trials (e.g. Allport et al. 1994; Meiran 2000; Rogers and Monsell 1995). This is true even when subjects are allowed long intervals between the cue and the stimulus in which to prepare for the upcoming task. The origins of this ‘residual switch cost’ continue to be debated. Some propose that it represents a stimulus-triggered control process that carries out the switch (Monsell et al. 2000; Rogers and Monsell 1995). Others suggest that it may reflect a carryover of inhibitory or facilitatory stimulus-response pairings from recent experience (Allport et al. 1994; Wylie and Allport 2000).

Some evidence used in this debate stems from studies of the interaction between task-switching and task-dominance. One counterintuitive finding has been the report that the costs of switching from a dominant to a non-dominant response are smaller than the costs of switching in the reverse direction (Allport et al. 1994). This has been interpreted as suggesting carryover of the inhibitory set from the prior trial. A non-dominant response in the prior trial requires strong inhibition of the dominant response. If a switch is then made, carryover of inhibition to the next trial will delay a dominant response. On the other hand, little inhibition is needed to perform a dominant response, resulting in minimal carryover and delay of a following non-dominant trial after a switch in this direction. However, it appears that reduced switch cost for non-dominant responses is not universal, but depends upon the nature of the task (Monsell et al. 2000). Although the reasons for this variation are not entirely clear, Monsell and co-workers suggest that one factor may be the degree of asymmetry in dominance, with asymmetric switch costs only emerging when dominance is itself strongly asymmetric. In this regard, the extreme degree of dominance asymmetry in the antisaccade/prosaccade relation affords an ideal opportunity to test this prediction.

As indicated by Monsell et al., task-switching can involve numerous dimensions: “which locus to attend to, which attribute of the stimulus to attend to, which response mode and values to get ready, what classification of the relevant stimulus attribute to perform, how to map those classes to response values...” (Monsell et al. 2000). Isolating these factors would seem a desirable step in identifying the key attributes of task-switching reflected in switch costs. In this regard, the antisaccade paradigm offers considerable advantages. The stimulus that triggers both prosaccades and antisaccades is identical. It is a small peripheral spot of light, with the same relevant attribute (spatial location) and classified in the same manner (right or left). Both tasks require the same response mode (an eye movement) with two possible response values (right or left saccade). The key difference remaining is the stimulus-response mapping, which is reversed for antisaccades compared to prosaccades. Hence, if asymmetries between switching to antisaccades and switching to prosaccades are found, this would be strong evidence that the carryover of inhibitory influences from the prior trial is generated at the level of stimulus-response mapping in the multistepped process of task-switching.

Another issue of interest in the interaction of task-dominance and task-switching is that of independence. Models of task-switching tend to treat the effects from current and prior trials as independent (Meiran 2000). If these processes are indeed independent, the accuracy rate of a response that requires both functions (the switched antisaccade) should equal the product of the accuracy rates of each function in isolation (a switched prosaccade, and a repeated antisaccade) (Schweickert 1985). The possibility that these are not independent is raised by the fact that damage to similar prefrontal areas impairs both task-switching (Stuss and Benson 1984) and antisaccade performance (Guitton et al. 1985).

A last point of note is that of ‘mixed-list costs’ (Los 1999; Meiran 2000). Even without a switch from the preceding trial, the repeated trials in a block of mixed-tasks may differ from trials in a single-task block, where only one response type is needed (Los 1999). Thus, estimates of costs may differ between studies that use single-task blocks as their baseline (Allport et al. 1994; Jersild 1927; Spector and Biederman 1976) and those that use repeated trials from a mixed-task block design (Rogers and Monsell 1995). Rogers and Monsell (1995) state that the latter are a more appropriate baseline, since there are confounding factors such as increased working memory load and arousal in mixed-task blocks compared to single-task blocks. Wylie and Allport (2000) argue that the recent performance of one response type has long-lasting delaying effects on the performance of an alternate response type. This ‘task-set inhibition’ or ‘negative priming’ may therefore affect not only switched but also repeated responses in a mixed-task block. This effect would be much smaller or non-existent in a single-task block, which therefore may be the more appropriate baseline. Again, testing for the existence and magnitude of mixed-list costs in a paradigm restricted to stimulus-response re-mapping would be of interest in this debate, especially as mixed-list costs have seldom been measured (Wylie and Allport 2000) (but see Los 1996, 1999).

We tested participants using both single-task blocks and mixed-task blocks that contained random sequences of antisaccades and prosaccades. To identify mixed-list costs we measured directional accuracy and latency differences between the single-task blocks and the repeated trials of the mixed-task blocks. To identify task-switch costs we measured differences in the same parameters between the switched and repeated trials within the mixed-task blocks. We hypothesized that latency task-switch costs would be smaller for antisaccades than for prosaccades. We used accuracy rates to test the hypothesis that switching and antisaccade performance are independent, with multiplicative interactions between their costs.

Materials and methods

Participants

We recruited 22 participants, 4 of whom (3 females and 1 male) withdrew from the study. Of the 18 participants tested, 6 were male and 12 female, ranging in age from 13 to 54 years with a mean of 30.8 years (SD=9.5). The participants had from 8 to 30 years of education, with an average of 17.3 years (SD=4.6). Fourteen were right handed. None of the participants had previously performed an antisaccade task. In a pre-test screening by telephone, none of the participants reported past or current episodes of neurologic or psychiatric disorders, such illnesses in their biological family, or any alcohol or substance dependence or abuse within the past 6 months. The mean ANART (Blair and Spreen 1989) estimate of the participants’ verbal IQ was 107 (SD=14).

Participants also completed two tests of sustained attention. One was a modified version of the Vigil Continuous Performance Test (The Psychological Corporation, Harcourt Brace & Co., 1998), in which participants watched a series of letters flashing on a screen and pressed the space-bar on the keyboard whenever they saw the letter ‘K’. The test was modified in such a manner that the time interval between the letter appearances was increased from the default of 900 ms to 1100 ms. A participant’s mean reaction time on the modified Vigil was 423 ms (SD=64), and accuracy was 98% (SD=2.4). They then completed a reaction time measure, which was an abbreviated version of the California Computerized Assessment Package (CalCAP) (Miller et al. 1991). All the stimuli in CalCAP were digits (Arabic numerals), and the test consisted of four sections. In the first, participants pressed the space-bar as soon as they saw any stimulus appear in the centre of the computer screen. In the second they responded only when they saw the digit 7, ignoring other stimuli. In the third, they pressed the space-bar when the same digit appeared twice in a row. In the final section, they responded when two consecutive digits appeared in sequence (e.g. 3 followed by 4).

All participants read and signed the informed consent familiarizing them with the purpose of the study, its protocol and possible risks and discomforts. The study was approved by the institutional review board of our hospital. Each participant received a payment for the study, which included a small incentive for every correct response.

Apparatus and eye movement protocol

We recorded eye movements with a magnetic search coil technique, using a scleral contact lens and a 3-foot field coil (Crist Instruments, Bethesda, MD). A participant’s head was secured in a chin rest with the cornea 81 cm away from a tangent screen. Displays were generated by a Power Macintosh 9600/233, using programs written in C++ on the Vision Shell programming platform (www.kagi.com/visionshell), and backprojected with an Eiki LC-7000U projector. The lens was placed in the left eye. We calibrated the system by having participants fixate nine targets in a square grid spanning 50°. Twelve data points were collected at each of nine targets, and a regression method was used to find the best linear fit. Eye position was digitized at 500 samples/s. A five-point central difference algorithm (Bahill and McDonald 1983) was used to derive velocity from eye position.

The initial display that the participants saw had a dark background with a white fixation ring at the centre, of 1° diameter and a luminance of 20 cd/m^2. The fixation ring was flanked by two dots of 0.7° diameter and the same luminance at 20° eccentricity right and left, which remained visible throughout the test. Participants were required to look at the fixation point at screen centre (Fig. 1): each trial began when a subject’s eye fell within 3° of the fixation point. After a period randomly varying between 1 and 1.5 s, the fixation point was replaced by one of two symbols – a yellow ‘O’ with a surrounding ring of 4.5°, or a blue ‘X’ spanning 4.5°. The yellow ‘O’ was the prompt for prosaccades, and the blue ‘X’ was the prompt for antisaccades. The prompts lasted 300 ms and were then replaced by the white fixation ring. After a mean interval of 2 s[1] (range 1850–2150 ms) the fixation ring disappeared and reappeared around one of the two peripheral dots, the side randomly determined. The subject was to make either a pro- or an antisaccade as quickly and accurately as possible, depending on the prior prompt. The white ring remained in the peripheral location until either the subject’s eye had fallen within 3° of the desired end position or 10 s had elapsed, then it reappeared at the central fixation point for the next trial.

Single-task blocks had 26 trials, either all pro- or all antisaccades. Mixed-task blocks had 52 trials, a random mix of pro- and antisaccades. Each block was repeated 4 times, thus generating about 104 trials of each type. For the mixed-task trials, about half required similar (repeated) and half required different (switched) responses from the previous trial. Blocks were given in a counterbalanced order to mitigate against effects of learning and fatigue, although it has been claimed that there is little practice effect on antisaccadic latency or angular error (Hallett 1978). All participants began with two single-task blocks and one mixed-task block. Half began with a block of prosaccades, then a block of antisaccades, followed by a mixed-task block, and the other half started with a block of antisaccades, then a block of prosaccades,

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[1] Prior studies showed that switch costs in latency decreased if the prompt was available before the stimulus (Shaffer 1965, 1966; Weber 1995), presumably because some of the reconfiguration of the system can be performed in advance. Advance reconfiguration appears to be complete by about 200–600 ms (Allport et al. 1994; Rogers and Monsell 1995; Weber 1995), leaving a smaller, asymptotic latency difference, which has been designated the ‘residual task shift cost’ (Rogers and Monsell 1995). Our prompt-to-target interval of 2 s clearly gave ample time for completion of advance reconfiguration, allowing us to focus on residual task-switch cost.

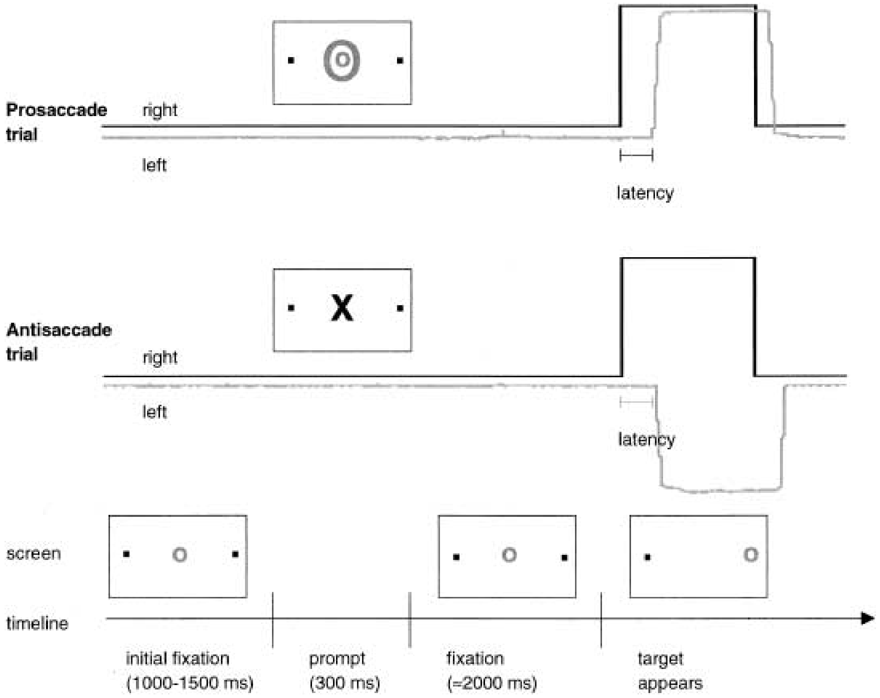

Fig. 1 Trial illustration. Progress over time is from left to right. *Top lines* show horizontal position traces of targets (*black lines*) and eyes (*grey lines*) for a correct prosaccade (*PS, top*) and antisaccade (*AS, below*). Rightward motion is shown as up, by convention. *Bottom diagrams* show what the screen shows at each interval. The trial begins with a fixation period, with the eyes and target (*ring*) at zero position, or mid-screen. *Two small dots* mark the two possible right and left locations of the target at all times. At the prompt, different screens are shown for prosaccades and antisaccades. The former are cued by a yellow double ring, the latter by a blue cross. The fixation screen then returns, followed by the appearance of the target, which triggers an eye movement response, either toward (prosaccade) or away from (antisaccade) the target. The trial is terminated when the eye enters a zone surrounding the desired eye location

followed by a mixed-task block. The order of the three tasks was then reversed. The entire sequence of six blocks was repeated once more. In total there were 12 blocks, between which short rests were provided.

Prior to testing, the design and the tasks were explained to each participant. Participants were instructed to look directly at the central fixation point, until a target appeared in the periphery. They were told that prior to the appearance of a peripheral target they would see a prompt, either a yellow ‘O’ or a blue ‘X’, flashed at the central fixation point. They were to look at the peripheral target if it was preceded by a yellow ‘O’, and to look at the white dot on the opposite side of the target (with respect to central fixation) if a blue ‘X’ preceded it. Before the test, all participants performed a practice session of 20 trials of each of the three different blocks. Participants were given a small monetary incentive for correct responses, to maintain motivation.

Analyses

We identified saccades as eye movements with velocities exceeding 46.9°/s. The onset of a saccade was taken as a point at which the velocity of the eye first exceeded 31.3°/s, and the end of a saccade as a point where the eye’s velocity fell below this baseline. For each saccade we recorded directional accuracy with respect to the required response (antisaccade vs prosaccade), and latency from target onset for the directionally correct responses only.

We divided the trials within the mixed-task blocks into two categories. One was the ‘repeated trials’, which were preceded by a trial requesting the same response (e.g. antisaccade preceded by an antisaccade). The other was the ‘switched trials’, which were preceded by a trial requesting a different response (e.g. antisaccade preceded by a prosaccade). Consequently, there were three conditions – Blocked (from single-task blocks), Repeated, and Switched – for both pro- (PS) and antisaccades (AS), yielding six different saccade conditions.[2]

The first saccade of each block was eliminated from the analysis. All other responses were sorted by directional accuracy, and mean accuracy rate was calculated for each subject on each of the six saccade types. Next, means and standard deviations for latency on correct trials only were calculated for each subject.

We made two sets of comparisons. First, to identify mixed-list costs we compared accuracy and latency between the single-task blocks and the repeated trials in the mixed-task blocks, using paired *t*-tests. Second, to identify residual switch costs we compared accuracy and latency between repeated (r) and switched (s) trials in the mixed-task blocks, for both prosaccades and antisaccades.

To test the hypothesis of independence of functions, we examined the accuracy data from the residual task-switch analysis. Since a correct response on an ASs (switched Antisaccade) trial requires both a correctly performed task switch and a correctly performed antisaccade, independence implies that the proportion of correct ASs responses should be equivalent to proportion correct (ASr, repeated Antisaccade) multiplied by the proportion correct (PSs, switched prosaccade) (Schweickert 1985). Thus, for accuracy: ASs=ASr·PSs. If, on the other hand, the likelihood of success in switching is affected by the direction in which a switch is made (to dominant vs non-dominant), or if the probability of success on one function (switch) influences the probability of success

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[2] A second division of mixed-task trials is also possible, based upon not only what was required but also what was actually performed in the preceding trial. This analysis confined itself to trials preceded by trials with directionally correct responses, yielding smaller numbers of repeated and switched trials. Our results with this second type of analysis were very similar to those of the first analysis, presumably because errors compose a minority of responses. Only the data from the first analysis are described in the results.

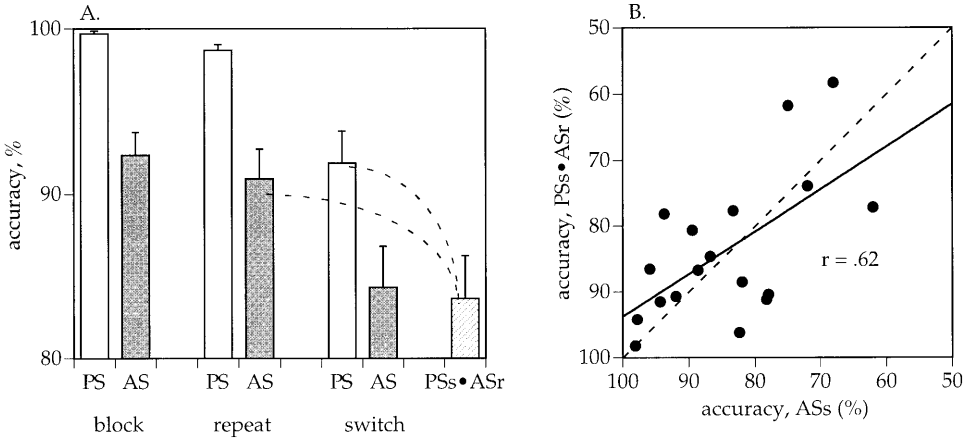

Fig. 2A, B Error costs. **A** Mean accuracy for prosaccades (*PS*) and antisaccades (*AS*) under the three different conditions. 'Block' data are from single-task blocks, 'repeat' and 'switched' data from mixed-task blocks: repeated trials are those with the same type of response requested in the prior trial (e.g. antisaccades preceded by an antisaccade), and switched trials are those with the other response requested in the prior trial. The 'PSs·ASr' column is the mean of the product of the accuracy rates of switched PS and repeated AS. If task-switching and antisaccades are independent, this should equal the switched AS cost in the adjacent column. *Error bars* are 1 SE. **B** Linear regression of the switched AS cost (*ASs*) with the product PSs·ASr across all subjects, indicated as a *solid line*. Independence predicts a line with slope of 1 and intercept of 0 (*dashed line*)

Table 1 Definition of relative effects

	Single-task Block	Mixed-task			Mixed-list Costs	Residual Switch costs
		Repeat	Switch			
Prosaccade (PS)	A	B	C	For PS	B–A	C–B
Antisaccade (AS)	D	E	F	For AS	E–D	F–E
Antisaccade (AS) costs	D–A for block	E–B for repeat	F–C for switch			

on the other (antisaccade), the effect will deviate from a multiplicative interaction.

We used a paired *t*-test to compare the accuracies of ASs to ASr·PSs, the hypothesis implying that there should be no significant difference. To test this hypothesis more stringently across individual subjects, we also performed a linear regression on the error rate of ASs versus the error rate predicted from the product of ASr and PSs. (Error rates rather than accuracy rates were chosen since intercept estimates are more meaningful when data are clustered near zero, as with error rates, than around 100%, as with accuracy rates.) A regression with a slope of 1 and an intercept of 0 would be consistent with independence.

We also calculated the antisaccade cost for blocked, repeated, and switched responses by subtracting the means of prosaccades from those of antisaccades in all these conditions (Table 1).

Results

Mixed-list costs (comparison of trials from single-task blocks with repeated trials from the mixed-task blocks)

The accuracy rate for blocked prosaccades was 99.7%, not significantly different from 100% (Table 2). Compared to blocked prosaccades, repeated prosaccades in the mixed design showed a significant 1% (SD=1.7) decline in directional accuracy (*P*=0.02). While there was a similar mean 1.45% (SD=5.5) difference for antisaccades, the greater variability of antisaccade performance rendered this insignificant (*P*=0.27) (Fig. 2A).

Table 2 Group accuracy results (means and standard errors, %)

	Single-task Block	Mixed-task	
		Repeat	Switch
Prosaccade	99.7 [0.2]	98.7 [0.4]	91.9 [1.9]
Antisaccade	92.4 [1.4]	90.9 [1.8]	84.3 [2.5]

The latencies of repeated prosaccades were 8 ms (SD=16) longer than blocked prosaccades, a difference that just failed to reach significance (*P*=0.056).[3] For antisaccades, the difference between blocked and repeated responses was an insignificant 3 ms (SD=19). The AS cost in the blocked condition (68 ms, SD=34) was not significantly different from the AS cost for repeated trials in the mixed-task blocks (64 ms, SD=32) (Table 3, Fig. 3A).

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[3] As a further test of Wylie and Allport's (2000) hypothesis that repeated trials are influenced by more remote task-switches, we also examined repeated prosaccades, comparing those in which the two prior trials were both prosaccades (i.e. a sequence of PS-PS-PS) and those in which a switch had occurred from the second-to-last trial (i.e. a sequence of AS-PS-PS). The accuracy for the PS-PS-PS sequence was 99.6%, compared to 97.7% for the AS-PS-PS sequence. The latency for the PS-PS-PS sequence was 231 ms (SD=71), compared to 236 ms (SD=88) for the AS-PS-PS sequence (*t*-test, *P*=0.36). Thus these remote effects within the mixed-task blocks are not significant for latency.

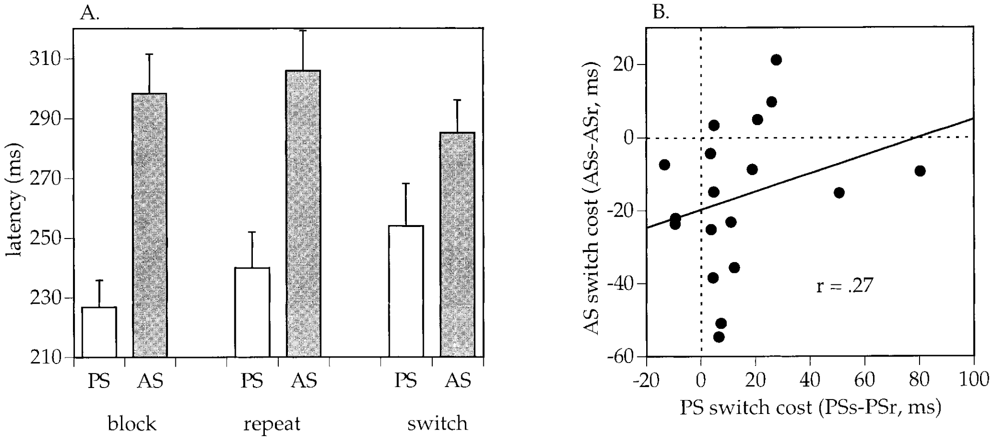

Fig. 3A, B Latency costs. **A** Mean latencies for prosaccades (*PS*) and antisaccades (*AS*) under the three different conditions. *Error bars* indicate 1 SE. Note that the mean atency of switched antisaccades is paradoxically shorter than that of repeated antisaccades. **B** Correlation of the switch cost for task switching (mean difference of switched minus repeated trials) for prosaccades versus antisaccades. No significant relationship is demonstrated

Table 3 Group latency results (means and standard errors, ms)

	Single-task Block	Mixed-task			Mixed-list Costs	Residual Switch costs
		Repeat	Switch			
Prosaccade (PS)	226 [8]	234 [10]	247 [13]	For PS	8 [4]	14 [5]
Antisaccade (AS)	294 [11]	297 [11]	281 [11]	For AS	3 [5]	(–) 16 [5]
Antisaccade (AS) costs	68 [8] for block	64 [8] for repeat	34 [8] for switch			

Residual switch costs (comparison of switched with repeated trials, both from the mixed-task blocks)

Directional accuracy

Task-switch lowered the accuracy of prosaccades by 6.8% (SD=8.2, $P<0.002$) and of antisaccades by 6.6% (SD= 10.6, $P<0.01$) (see Table 2). The multiplicative analysis revealed that the ASr·PSs accuracy rate was not significantly different from the actual accuracy rate of switched antisaccades – ASs ($t=0.76$, $df=17$, P=NS). The linear regression analysis of ASs versus ASr·PSs yielded a function with significant correlation ($r=0.62$, $df=16$, $P<0.007$), slope of 0.65 and intercept of 6.2 (Fig. 2B); these values do not differ significantly from a slope of 1 ($P=0.14$) and an intercept of 0 ($P=0.85$). The slope does differ significantly from 0 ($P<0.006$). These results are consistent with the hypothesis that these are independent effects.

Latency

Task-switching increased latency of prosaccades by 14 ms (SD=22, $P<0.02$). However, antisaccades showed the reverse relationship: switching reduced latencies by an average of 16 ms (SD=20, $P<0.004$). Thus, rather than a switch cost, there was a switch benefit for antisaccades. This paradoxical reduction occurred in 14 of 18 subjects (Fig. 3B). The result of these contrasting effects of task-switching was to reduce the antisaccade cost from 64 ms (SD=32) in the repeated trials to only 34 ms (SD=35) in the switched trials (Table 3, Fig. 3A).

These data also reveal an interesting discrepancy between the costs of an antisaccade and a task-switch. The antisaccade latency cost, represented by the difference between repeated anti- and repeated prosaccades (64 ms), is 4 times greater than the latency cost of switching, represented by the difference between switched and repeated prosaccades (14 ms). This stands in distinction to the finding that the directional accuracy costs of antisaccades and task switching are the same, about 7%. This suggests that AS and switching are equally likely to be performed correctly, but the operations incurred by AS preparation are much more time-consuming than those incurred by task-switching.

Correlations of the paradoxical switch effect in antisaccade latency

To further investigate this surprising paradoxical effect of task-switching on antisaccade latency, we performed several additional correlation analyses. We first considered whether the unexpected reduction in antisaccade latency in the task-switch condition might be due to a speed/accuracy trade-off. It is possible that certain participants were for some reason primed to make more rapid responses to the antisaccade prompt when it followed prosaccade trials than when it followed antisaccade trials. If so, the subjects with greater paradoxical task-switch reductions in latency for antisaccades should show lower accuracy for switched antisaccades as well. However, no such correlation was found ($r=0.05$, P=NS, Fig. 4).

Another possibility is that, rather than a switch cost from the prior trial, there was a ‘prior-antisaccade effect’ overriding any switch cost. That is, perhaps an antisaccade in the previous trial increased the latency of

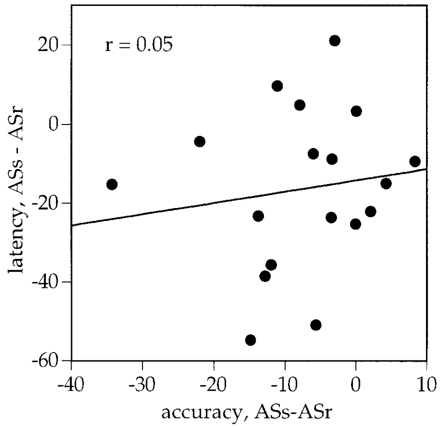

Fig. 4 Relation of error cost to latency cost for task switching of antisaccades. The difference between switched and repeated antisaccades in latency is plotted against the difference between switched and repeated antisaccades in error rate. If a speed/accuracy trade-off is present, there should be a significant negative correlation. There is not

the next response by about 15 ms, regardless of whether the current response was a prosaccade or antisaccade. If so, the switch effect on antisaccades might be negatively correlated with the switch effect on prosaccades (i.e. [ASr–ASs]=–[ASs–ASr]≈[VSs–VSr]). However, this analysis did not yield significant correlations either (r=0.27, P=NS) (Fig. 3B).

Last, we considered the possibility that the paradoxical switch effect for antisaccades was related to other non-specific attentional factors. We correlated the two switch effects (for antisaccades and prosaccades) and the two antisaccade effects (for repeated and switched trials) with various measures of attention and vigilance from the Vigil and CalCAP tests. The paradoxical switch effect for antisaccades had significant correlations with the mean Vigil reaction time, averaged over all blocks, the choice reaction time and the sequential reaction time part 2 of the CalCAP (Table 4). The shorter the reaction times on these tests, the smaller the difference between switched and repeated antisaccade latencies (Fig. 5).

Table 4 Correlation of saccadic effects with manual reaction times. Superscripts indicate values of significant correlations. Positive correlations in latency data imply that faster esponses or lesser costs on eye movement tasks correlate with faster responses on attention tasks. Positive correlation for accuracy implies that greater accuracy or lesser costs on eye movement tasks correlate with faster responses on attention tasks

	Vigil	CalCAP			
		Simple	Choice	Sequential 1	Sequential 2
A. Latency					
PSr	0.19	$0.61^{0.01}$	$0.54^{0.02}$	0.21	0.02
Switch cost, PS	0.24	0.35	0.21	0.04	0.09
Switch cost, AS	$-0.53^{0.02}$	0.01	$-0.57^{0.01}$	–0.39	$-0.6^{0.008}$
AS cost, repeat	0.09	–0.17	0.16	0.11	0.35
AS cost, switch	–0.38	–0.37	–0.31	–0.15	–0.09
B. Accuracy					
PSr	$0.72^{0.0008}$	$0.47^{0.05}$	0.22	–0.44	0.41
Asr	–0.38	–0.17	0.45	0.29	0.13
Switch cost, PS	–0.05	0.04	0.14	–0.01	0.19
Switch cost, AS	–0.06	0.03	0.32	0.06	0.15

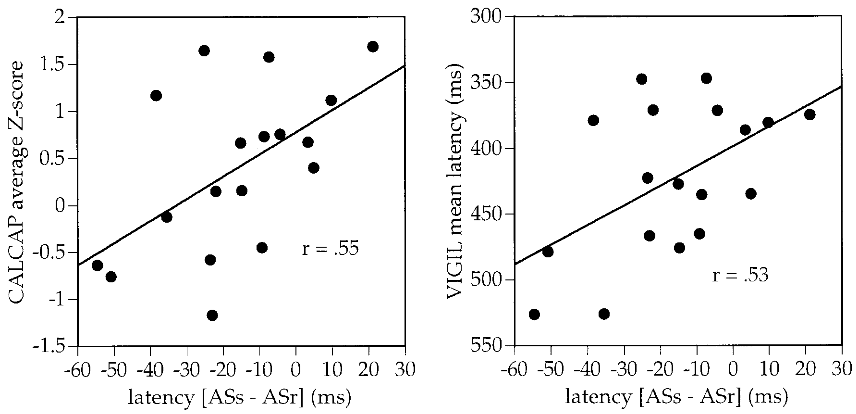

Fig. 5A, B Relation of the task-switch effect on antisaccadic latency to attentional measures. The same latency switch cost for antisaccades in Figs. 3B and 4 is plotted against the manual reaction time data from the CalCAP **(A)** and Vigil **(B)** tests, For the CalCAP, the mean z-score for all four subtests is plotted – a positive z-score corresponds to a shorter manual reaction time. For the Vigil, the mean reaction time including all four blocks is plotted. Note that both graphs have the y-axes arranged so that faster reaction times are *towards the top*. For both, the faster the manual reaction time (the greater the vigilance), the less the reduction in antisaccadic latency with task switching

None of the other error or latency costs correlated with any attentional measures. As expected, the baseline latency and also error rate of repeated prosaccades positively correlated with simple and choice reaction times on the CalCAP.

Discussion

We found that the accuracy rate of task-switching (i.e. the accuracy rate of switched prosaccades) and the accuracy rate of antisaccade performance (i.e. the accuracy rate of repeated antisaccades) were similar, about 92%. Thus the accuracy costs of task-switching and antisaccade performance are equivalent. Furthermore, the accuracy costs of task switching and of antisaccade performance are multiplicative. The product of the accuracy rates when each executive function was performed alone (i.e. switched prosaccades and repeated antisaccades) correlated highly with the accuracy rate when both functions were required in a single response (i.e. switched antisaccades). The regression was not significantly different from a line with a slope of 1 and an intercept of 0. This is consistent with independence of current-trial dominance effects from prior-trial (switching) effects.

The latency data, however, show differences in the costs of switching and antisaccade performance, with the latter nearly 4 times the former. More importantly, they confirm asymmetries in switching to non-dominant (antisaccade) versus dominant (prosaccade) tasks. However, this asymmetry is extreme, with reversal of cost to show a paradoxical benefit of task-switching in antisaccade latencies. This benefit is reduced in subjects who are more attentive, with shorter manual reaction times on tests of vigilance and attention. It does not appear to be due to a speed/accuracy trade-off, and does not correlate with the switch effect for the dominant prosaccade response.

In contrast to these effects for residual task-switch costs, the mixed-list costs (comparison of trials from single-task blocks with repeated trials from the mixed-task blocks) were either minimal, for prosaccades, or insignificant, for antisaccades.

Antisaccade costs

Our antisaccade costs are similar to those previously reported (see Everling and Fischer 1998 for review). All prior studies found that antisaccades have longer mean latencies and greater error rates than prosaccades, similar to other task pairs with dominant/non-dominant task asymmetries. Reported antisaccade latency costs vary widely, from 34 to 185 ms (Fukushima et al. 1990; Guitton et al. 1985; Kitagawa et al. 1994; Lasker et al. 1987; Lueck et al. 1990; Munoz et al. 1998; Reuter-Lorenz et al. 1995; Thaker et al. 1989; Forbes and Klein 1996), which may reflect variations in design elements such as warning cues, performance incentives, and the predictability of fixation periods or target amplitudes. The largest study, with 168 subjects, found that between the ages of 15 and 79 years antisaccade latency costs remain stable at about 50–80 ms, as does error rate, at about 10% (Munoz et al. 1998). Our data are consistent with these estimates.

Mixed-list costs

Rogers and Monsell (1995) raised the concern that comparisons between responses in single-task blocks and those in mixed-task blocks do not isolate the true task switch cost, but include costs from non-specific factors such as vigilance and working memory. A similar charge could be made against antisaccade studies, which tend to use single-task block designs. Our comparison between block trials and repeated trials was aimed at measuring mixed-list costs (Meiran 2000), which, as Wylie and Allport (2000) note has seldom been done. For saccades, there was at most a 1% decrease in accuracy, small compared to the accuracy costs for task-switching and antisaccade performance (both about 7%). Also, we found a trend to an 8-ms increase in prosaccadic latency, but no significant effects on antisaccade latency or accuracy. While this might suggest an asymmetric effect, with a slight cost for dominant but not for non-dominant responses, the greater variability of the measures for antisaccades may have masked an effect of the magnitude found for prosaccades.

The chief conclusion of this analysis is that the effects of non-specific factors recruited by mixed-task over single-task blocks are either small or non-existent. Our data show that this has little impact upon the calculation of the error costs of either task switching or antisaccade performance. For latency too, the 8-ms increase in prosaccade latency in repeated trials is almost a magnitude smaller than the antisaccade latency costs of around 60 ms. Thus, these data validate the cost estimates from previous single-task block studies of antisaccades. However, the effect on latency costs for task switching is more problematic, because the estimated task-switch cost is also small, around 13 ms. If there is a true mixed-list cost of around 8 ms, then studies that use a single-task block as a baseline measure may overestimate task-switch latency costs by up to 50%, if their residual switch cost is in the same range as ours. Indeed several prior studies have obtained estimates of task-switch costs in the range of 19–42 ms (Rogers and Monsell 1995; Shaffer 1965; Stablum et al. 1994).

It should be stressed that our findings do not negate the possibility of mixed-list costs existing in other task-switch paradigms. As mentioned, the antisaccade paradigm has appeal because it consists primarily of a stimulus-response re-mapping, without changes in stimulus, relevant stimulus dimension, or response mode, among other factors. Tasks that do contain such factors may be more demanding and incur mixed-list costs. Rather, our results indicate that stimulus-response re-mapping does not generate substantial mixed-list costs.

Interactions between task-switch and antisaccade performance

We find that the influences of task-switching on the accuracy of antisaccades and prosaccades are similar, multiplicative, and therefore likely independent. This accords with the data of a smaller antisaccade study (Weber 1995), though the results were not described in this fashion. In contrast, another task-switching study using an antisaccade paradigm (Hunt and Klein 2002) found no difference between the accuracy rate of switched and that of repeated trials, for both prosaccades and antisaccades. This difference in findings may be explained by that study's use of a predictable sequence of trial types, though their subjects reported no awareness of the sequence. Otherwise, not much attention has been paid to accuracy rates in the task switch literature. Latency effects, however, have been researched intensively (e.g. Monsell et al. 2000; Wylie and Allport 2000). A number of prior investigations of other dominant/non-dominant tasks have shown asymmetric latency effects of task-switching. Pre-eminent among these are a series of studies of the Stroop effect by Allport and colleagues, showing that the latency of the dominant response (word reading) is increased by task-switching more than the latency of the non-dominant response (colour naming) (Allport et al. 1994; Wylie and Allport 2000).

However, this has not been found for all dominant/non-dominant task pairings (Monsell et al. 2000). Monsell and colleagues have shown that this asymmetry can be eliminated by manipulations that make the dominant task harder, such as degrading the quality of the text in the Stroop task. Of note in this regard is a comparison of our results with a prior small antisaccade study that found an equal task-switch increase of 35 ms for both prosaccades and antisaccades (Weber 1995). This study differed from ours by the use of five well-trained observers who performed many antisaccade trials over the course of the study. The discrepancy with our results may stem from strengthening of antisaccade stimulus-response mappings through extensive intra-experimental practice in that study.

The competing explanations of task-switch processes all have in common the assumption that any stimulus-response combination in a current trial obtains an advantage from having the same stimulus-response mapping in the prior trial. While a smaller task-switch cost for moving from dominant to non-dominant tasks than in the reverse direction is best explained by theories invoking inhibition by the prior task-response set in the N-1 trial (Allport et al. 1994), or stimulus-cued retrieval of prior associative learning (Wylie and Allport 2000), none of the current theories can account for a paradoxical reduction in latency for task-switched antisaccades, the non-dominant response in our study. Though small, the paradoxical switch benefit for antisaccades we found is consistent across subjects, being present in the majority. We have also replicated it in studies of schizophrenic patients (Manoach et al. 2002) and patients with developmental right hemispheric learning disability (unpublished observations). Another group has also recently noted paradoxical latency benefits with task-switching, but for both antisaccades and prosaccades, using a predictable sequence paradigm (Hunt and Klein 2002). There are at least two possible reasons why this paradoxical reduction may have only emerged in an antisaccade study of task-switching. One invokes a matter of degree, that the antisaccade/prosaccade pairing is among the most extreme examples of dominance asymmetry. The other reflects the fact that, unlike tasks such as the Stroop test, the antisaccade task involves only a stimulus-response re-mapping, without any change in the stimulus attribute attended or its classification. Latency effects from these additional switches could mask a paradoxical latency benefit from stimulus-response re-mapping to the non-dominant response.

How could a paradoxical reduction in latency arise? There are at least two possible explanations. First is that, rather than a task switch cost, there may be a 'non-dominant stimulus-response mapping cost' carried over from the prior trial, affecting both prosaccades and antisaccades. Thus an antisaccade stimulus-response mapping in the prior trial may inhibit the saccade system in general in the current trial. Although we could not demonstrate a correlation between task switch costs of prosaccades and switch costs for antisaccades, this does not entirely exclude this possibility, given the magnitude of the within-subject variance in saccadic latencies. If this paradoxical switch effect is due to a remote antisaccade effect from the N-1 trial, though, it does not appear to be directly related to the antisaccade effect in the current trial, for two reasons. One is the demonstration of independence of task-switch effects and antisaccade effects in the accuracy data. The second is the fact that in our other study (Manoach et al. 2002) schizophrenic patients showed markedly increased antisaccade latency costs but no difference in the paradoxical task-switch effect in latency, indicating that the antisaccade latency can be impaired selectively, independent of task-switch latencies.

Second, rather than a general detrimental antisaccade effect carrying over from the prior trial, it may be that the operation of a second cognitive function like task-switching truly facilitates the execution of non-dominant responses like antisaccades specifically, and yet delays habitual responses such as prosaccades. Some support for this can been found in a recent study of antisaccades performed simultaneously with an attentionally demanding perceptual discrimination task (Kristjansson et al. 2001). These authors suggested that other attentional tasks inhibit reflexive responses, thus both delaying them and also facilitating non-dominant responses. In our study, the possibility of an attentional basis to this facilitatory effect on the non-dominant antisaccade response is indicated by the correlations showing that the effect is smallest in those subjects who are most attentive, with superior performance on our manual reaction time measures of vigilance. Thus, those subjects who are most alert and attentive may actually need to devote fewer resources to the secondary cognitive operation of task-switching, resulting in less facilitation of the primary operation of antisaccade generation.

Which of these two different accounts is responsible for this interesting effect of task switching on antisaccade latency requires further investigation.

Acknowledgements J.B. was supported by a grant from the National Institute of Neurological Disorders and Stroke (NINDS). Kristen Lindgren provided assistance with data analysis.

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