



## Knowing the future: Partial foreknowledge effects on the programming of prosaccades and antisaccades

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### ABSTRACT

Foreknowledge about the demands of an upcoming trial may be exploited to optimize behavioural responses. In the current study we systematically investigated the benefits of partial foreknowledge – that is, when some but not all aspects of a future trial are known in advance. For this we used an ocular motor paradigm with horizontal prosaccades and antisaccades. Predictable sequences were used to create three partial foreknowledge conditions: one with foreknowledge about the stimulus location only, one with foreknowledge about the task set only, and one with foreknowledge about the direction of the required response only. These were contrasted with a condition of no-foreknowledge and a condition of complete foreknowledge about all three parameters. The results showed that the three types of foreknowledge affected saccadic efficiency differently. While foreknowledge about stimulus-location had no effect on efficiency, task foreknowledge had some effect and response-foreknowledge was as effective as complete foreknowledge. Foreknowledge effects on switch costs followed a similar pattern in general, but were not specific for switching of the trial attribute for which foreknowledge was available. We conclude that partial foreknowledge has a differential effect on efficiency, most consistent with preparatory activation of a motor schema in advance of the stimulus, with consequent benefits for both switched and repeated trials.

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### 1. Introduction

Successful behaviour often requires the ability to respond rapidly and accurately to events occurring in the environment. Behavioural efficiency may be enhanced by exploiting foreknowledge about the upcoming task, which for the purposes of this study is defined as ‘completely reliable information about some or all properties of an upcoming trial from the historical context of previous trials’ (Barton, Kuzin, Polli, & Manoach, 2006b). Complete reliability distinguishes foreknowledge from prior-probability effects, in which a cue is often used to indicate that some property of the upcoming trial (e.g. a certain target location) has a certain likelihood of occurrence (e.g. (Carpenter & Williams, 1995; Dreisbach, Haider, & Kluwe, 2002; Schiller, Haushofer, & Kendall, 2004)). In foreknowledge, that likelihood is 100%; hence, foreknowledge can be considered a special class of prior-probability effects.

Foreknowledge may exert effects through influencing trial preparation. Another means of doing this is through pre-cueing, by providing information about what will be required in that trial,

with sufficient lead time before the appearance of the stimulus to allow subjects to use the cue to prepare. Although some investigators consider pre-cueing during the current trial a form of foreknowledge (Schiller et al., 2004), pre-cueing does not require use of information from trial history. Previous studies have shown that ‘extrinsic’ information from preceding cues and ‘intrinsic’ information based on foreknowledge from sequence information have different effects on behaviour, and hence should not be considered as equivalent (Barton, Greenzang, Hefter, Edelman, & Manoach, 2006a; Sohn & Anderson, 2003). In contrast to pre-cueing, which relies on information given within the trial, foreknowledge relies on information about the larger sequence, and thus can inform us on how working memory and contextual information from outside the confines of the current trial are used to influence behaviour. Contextual effects are highly relevant to real-life performance, given that our responses to the environment are not isolated acts but form part of a historical continuum of activity.

In the past, several foreknowledge studies have examined completely predictable tasks, in which the type of stimulus, the task-set, and the specific response required were all known in advance (Kingstone & Klein, 1993; Moschner & Zangemeister, 1993; Pare & Munoz, 1996; Schiller et al., 2004; Wegner & Fahle, 1999). Not sur-

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prisingly, under these conditions error rates and latencies were reduced and there were more anticipatory responses. Such results suggest that foreknowledge about upcoming events can be used to optimize behaviour and increase the efficiency of our responses to the environment. However, what is not yet known is whether all types of information about the upcoming event are useful for behavioural optimization, or if only certain information can be used to improve efficiency. To determine this requires studies with partial foreknowledge paradigms, in which only some aspects of the upcoming trial are known and others not. Such *partial foreknowledge* designs have not been used frequently. In a recently proposed taxonomy, partial foreknowledge was classified according to the type of information that can be determined ahead of time from trial history (Barton et al., 2006b). Thus one may know where the stimulus will appear (stimulus-location-foreknowledge), the type of task to be performed (task foreknowledge) or the specific response that will be required (response-foreknowledge).

This taxonomy leads to a number of simple questions regarding the potential influence of partial foreknowledge on behaviour: first, does partial foreknowledge enhance performance in the manner that complete foreknowledge does; second, is partial foreknowledge as effective in optimizing performance as complete foreknowledge; and third, do the different types of foreknowledge differ in their effects on behaviour. If the latter is answered in the affirmative, this may indicate that the contextual effects of foreknowledge may operate through selective effects on some but not all of the cognitive processes involved in saccade generation.

Thus, in this study we systematically compared the effects of partial foreknowledge of: (a) stimulus location, (b) task and (c) response, to baseline conditions in which there is either complete foreknowledge (all dimensions following a predictable sequence) or no-foreknowledge at all (all dimensions following random sequences). We used a saccadic paradigm, using prosaccades, in which the subject looks toward a suddenly appearing stimulus, and antisaccades, in which the subject looks in the opposite direction (Hallett, 1978; Hallett & Adams, 1980). For each of these three task dimensions there are two alternatives: (a) a right or left stimulus, (b) a prosaccade or antisaccade task, and (c) a rightward or leftward response. Without foreknowledge, any given trial may thus require one of four behaviours: a rightward prosaccade, a leftward prosaccade, a rightward antisaccade, or a leftward antisaccade. With partial foreknowledge of any one of the three dimensions, though, the set of possible behaviours is reduced by half. Thus, knowing that the stimulus will be on the right reduces the set of options to a rightward prosaccade and a leftward antisaccade. Knowing that the task will be an antisaccade reduces the set to a rightward and leftward antisaccade, while knowing that the desired response will be a rightward saccade reduces the set to a rightward prosaccade and a rightward antisaccade. Complete foreknowledge, of course, reduces the set of possible behaviours to one. We hypothesized that, compared to the no-foreknowledge condition, complete foreknowledge would significantly enhance performance, reducing latencies and error rates, while the effects of partial foreknowledge would be intermediate. We also hypothesized that the different forms of partial foreknowledge would differ from each other in their effects on saccades.

In addition to examining the effects of foreknowledge on saccadic performance, we included a secondary analysis on switch costs, the difference in performance between trials in which a particular dimension was changed and those in which it was repeated. Many studies on task-switching show that performance is better on trials that repeat the parameters of the prior trial, than those in which these are changed (Allport, Styles, & Hsieh, 1994; Meiran, Chorev, & Sapir, 2000; Monsell, Yeung, & Azuma, 2000; Rogers & Monsell, 1995). In part this is due to a need for ‘active re-configu-

ration of the response system when demands change in switched trials, which is reflected in switch costs (Monsell et al., 2000; Rogers & Monsell, 1995). If repeated trials are already performing optimally, then it may be that these will not benefit significantly from foreknowledge; rather, it may be that foreknowledge effects are particularly manifest on trials that require re-configuration. If so, this will be revealed as a significant reduction of switch costs in conditions with foreknowledge. As switching can involve either stimulus location, task or response, we investigated whether partial foreknowledge about any of these three dimensions allows the subject to reduce the added costs incurred by switching. As above, we explored the hypothesis that the different partial foreknowledge conditions would differ in their effects on switch costs. Furthermore, our paradigm allowed us to determine whether the benefits of partial foreknowledge about one particular dimension improved switching performance for that dimension alone, or if the benefit generalized to switching in all dimensions.

## 2. Methods

### 2.1. Subjects

10 healthy subjects, seven of whom were male, with median age 33.5 years (range 24–43) participated. All had normal or corrected-to-normal vision and viewed the stimuli with both eyes and uncorrected vision. None had a history of psychiatric or neurological disease. The protocol was approved by the institutional review boards of Vancouver General Hospital and the University of British Columbia, and all subjects gave informed consent in accordance with the declaration of Helsinki.

### 2.2. Eye movement apparatus and protocol

Subjects sat in dim illumination 57 cm away from a 22" NEC Multisync FE 2111SB monitor that presented stimuli at 85 Hz, with their heads stabilized by a chin-rest. Eye movements were recorded by a video-based eyetracking system (Eyelink 1000, SR Research Ltd, Mississauga, Canada). Stimuli, trials and experimental blocks were created with SR Research Experiment Builder 1.1.2. Each experiment started with calibration on the default 9-point grid, which was accepted if there was an angular error of less than 1° for each point tested. Between blocks the system was checked for offset error by having the subject fixate a target at screen center. If there was an offset error greater than 1°, we repeated the calibration with the 9-point grid.

Each trial started with a white fixation cross on a black background. After a randomly determined interval of 1s or 1.5s,<sup>1</sup> the fixation cross was replaced by an instructional cue, which was either a red ‘X’ spanning 2° of visual angle, indicating that an antisaccade was required, or a green circle with an inner diameter of 2° of visual angle, indicating that a prosaccade should be performed. Simultaneous with the instructional cue, the stimulus, a white ring of 20 pixels diameter (0.7° of visual angle), appeared either to the right or to the left on the horizontal meridian, at an eccentricity of 427 pixels (17° of visual angle). Both the stimulus and the instructional cue remained on the screen until the subject made a saccade with a minimum amplitude of 3° and an endpoint located within a radius of 150 pixels (6°) from the goal of the eye movement. Once this

<sup>1</sup> It is possible that making the timing of trial events also predictable may allow subjects to better synchronize preparatory processes. However, it is not clear whether this timing effect modulates all preparatory processes equally, and if not whether this should be considered a confound or a statistical advantage. Furthermore, paradigms with predictable timing have the disadvantage of increasing the number of anticipatory responses, and hence the number of rejected trials (Barton et al., 2006a).

occurred the screen display was replaced 500 ms later by the fixation screen for the next trial.

Trials were given in blocks of 41 trials. Before each foreknowledge block, subjects were informed about the nature of the predictable sequence that would be occurring in that block, if any. Each block was preceded by a practice block of 20 trials that were identical to the experimental blocks, and therefore also served to demonstrate the predictable or random sequences that would occur in that block. Blocks were divided into one of five conditions, depending on whether the stimulus location, task set, or response direction followed a random or predictable sequence within the block. Predictable sequences followed an AABB pattern, in which one value of the dimension occurred twice, and then the other value occurred twice. This generated both repetitions and switches of the values for that dimension, which could be contrasted to assess switching costs for that dimension (Barton et al., 2006a; Rogers & Monsell, 1995).

### 2.3. Conditions

1. The *no-foreknowledge* condition contained random sequences for all three parameters: stimulus location, task-set and response direction.
2. The *stimulus-location-foreknowledge* condition contained predictable AABB sequences of stimulus location (i.e. two left-hemifield stimuli followed by two right-hemifield stimuli), but random sequences of task-set and response direction.
3. The *task-foreknowledge* condition contained predictable AABB sequences of task-set (i.e. two prosaccades followed by two antisaccades), but random sequences of stimulus location and response direction.
4. The *response-foreknowledge* condition contained predictable AABB sequences of response direction (i.e. two leftward saccades followed by two rightward saccades), but random sequences of stimulus location and task-set. Thus, in this condition subjects would know the direction of the saccade they were supposed to perform, but they would not know whether this would be a prosaccade or an antisaccade, or whether the stimulus would be located on the left or the right.
5. The *complete-foreknowledge* condition had predictable sequences for all three parameters. However, it is not possible to construct complete foreknowledge blocks with AABB sequences for all three parameters. Rather, we constructed blocks with an AABB sequence for two of the parameters, with the third parameter held constant. Thus, for example, one predictable block had only left-hemifield stimuli, with an AABB sequence of task-set (prosaccade - prosaccade - antisaccade - antisaccade) and therefore an AABB sequence of response direction (left-left-right-right). There were six such *complete foreknowledge* blocks, two with stimulus location held constant (one with left hemifield and two with right-hemifield stimuli), two with task-set held constant (one with prosaccades only and one with antisaccades only), and two with response direction held constant (one with leftward saccades and one with rightward saccades).

For the conditions of *no-foreknowledge* and partial foreknowledge (*stimulus-location-foreknowledge*, *task-foreknowledge*, and *response-foreknowledge*), we presented two blocks of 41 trials for each condition. For the complete-foreknowledge condition, we presented one block of 41 trials for each of the six different blocks. While this gave us twice as many complete foreknowledge trials as in the other conditions, it provided us with equivalent numbers of switched and repeated trials from AABB sequences for the parameters of stimulus location, task-set and response direction, as in the partial foreknowledge conditions.

The experimental session was divided into two halves, each containing one block of the no-foreknowledge and partial foreknowledge conditions, and three of the six complete foreknowledge blocks. The order in the first half was randomly determined, with the order in the second half being the reverse of the order in the first half. Overall, the experiment contained 574 experimental trials per subject.

### 2.4. Data analysis

Data was analyzed using SR Research Data Viewer 1.7.5. Saccades were detected when eye velocity reached  $31^\circ/\text{sec}$ , acceleration exceeded  $9100^\circ/\text{sec}^2$ , and position changed by more than  $0.15^\circ$ . From the recorded data of each trial we analyzed the first saccade after stimulus onset with an amplitude  $> 3^\circ$ . Reaction time was calculated as the time from stimulus onset to saccadic onset. We excluded trials in which the first saccade (a) had a reaction time of less than 80 ms or more than 800 ms, (b) had a starting point greater than 50 pixels ( $2^\circ$ ) from screen center, or (c) had a mean trajectory more than  $45^\circ$  away from the horizontal meridian, with mean trajectory being the vector between starting point and endpoint of the saccadic eye movement. These exclusion criteria eliminated 14.1% of all trials (ranging from 5.7% to 17.6% between subjects). The remaining saccades were divided into correct and erroneous saccades, with correct saccades having a trajectory within  $45^\circ$  of the desired eye movement, and erroneous saccades having a trajectory within  $45^\circ$  of the alternate location in the other hemifield. To minimize the contribution of other phenomena like post-error slowing, only trials that were preceded by trials with correct saccadic responses were included in the analysis.

For each condition we calculated error rate as the number of erroneous saccades divided by the total number of eligible saccades. For latency we analyzed only the response times from directionally correct saccades. Of all trials 82.3% were included for this analysis. For prosaccades and antisaccades in each condition we calculated for each subject a mean accuracy and latency score. From these means we derived an inverse efficiency score. Since subjects can vary reaction time inversely with accuracy – the ‘speed-accuracy trade-off’ (Fitts, 1954) – performance may best be reflected in a single variable that combines the two. The inverse efficiency score does this by dividing latency by accuracy rate, resulting in an index that is lower for more efficient performance (Morein-Zamir, Chua, Franks, Nagelkerke, & Kingstone, 2007; Townsend & Ashby, 1983). We analyzed the impact of foreknowledge on inverse efficiency scores by using a general linear model with main factors of saccade type (prosaccade, antisaccade) and foreknowledge condition (none, stimulus location, task-set, response and complete), with subject as a random factor, using JMP 7.0.2 (SAS Institute Inc; www.jmp.com). We then used Tukey’s honestly significant difference (HSD) test at a significance level of 0.05 to identify significant pairwise contrasts.

We performed a second analysis on switch costs. For this we classified each trial on the basis of whether it repeated or switched each of the three dimensions in the prior trial: that is, whether it had the same or different stimulus location, task-set, or response direction as the preceding trial. Again, we only included trials in which the prior response had been correct. We calculated the mean latency and error rate for switched and repeated trials as above, and derived the inverse efficiency score for each switching dimension (stimulus location, task and response) and saccade type in each foreknowledge condition. Switch costs were then calculated by subtracting the inverse efficiency score for repeated trials from that for switched trials. We statistically analyzed these inverse efficiency-switch costs using a general linear model with main factors of saccade type (prosaccade, antisaccade), foreknowledge condition (none, stimulus location, task-set, response and

complete), and switching dimension (stimulus location, task, response), with subject as a random factor. Individual contrasts were investigated with Tukey's honestly significant difference (HSD) test at a significance level of 0.05 to identify significant pairwise contrasts.

### 3. Results

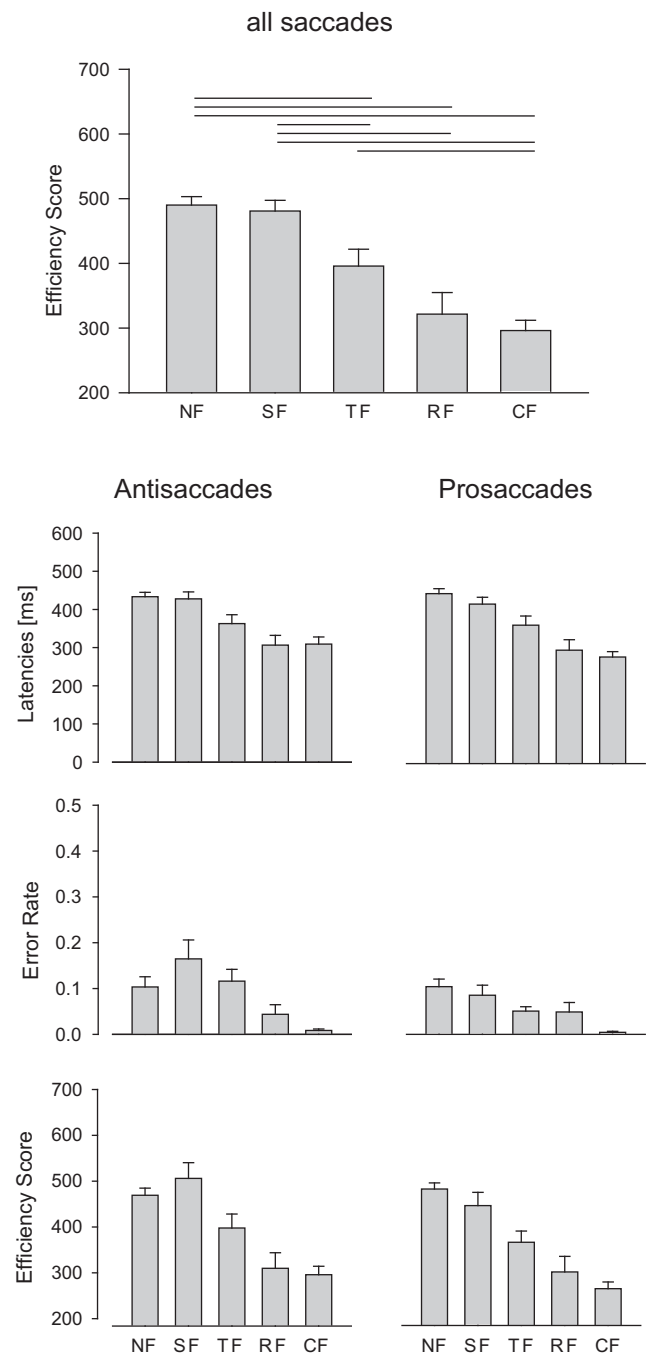
#### 3.1. Effects of partial foreknowledge on saccadic efficiency

There was a trend toward significance for saccade type ( $F(1,81) = 3.7, p = 0.057$ ), with longer reaction times for antisaccades than prosaccades. There was a main effect of foreknowledge condition ( $F(4,81) = 43.1, p < 0.0001$ ), but no significant interaction between saccade type and foreknowledge condition ( $F(4,81) = 0.95, p = 0.44$ ), indicating that there was no evidence that foreknowledge affected prosaccades and antisaccades differently. Collapsing across saccade type, Tukey's HSD test showed significant pairwise contrasts between all foreknowledge conditions, with the exception of contrasts between response-foreknowledge and complete-foreknowledge ( $F(1,81) = 1.62, p = 0.20$ ) and between stimulus-location-foreknowledge and no-foreknowledge ( $F(1,81) < 0.01, p = 0.99$ ). Thus knowing stimulus location does not improve saccadic efficiency over no foreknowledge at all, while knowing the direction of the response alone makes performance as efficient as knowing all aspects of the upcoming trial. Knowing whether the task is to be a prosaccade or an antisaccade results in an intermediate benefit: better than no knowledge at all but not as good as complete foreknowledge (Fig. 1).

#### 3.2. Effects of partial foreknowledge on switch costs

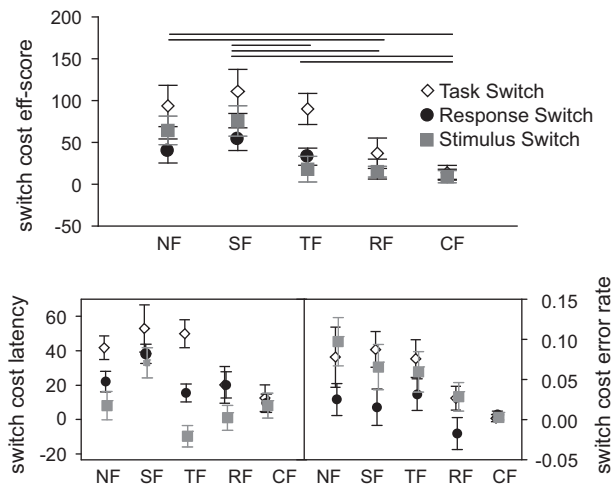
This analysis examined the effects of the different types of foreknowledge - in particular the three different types of partial foreknowledge (stimulus location, task, response) - and their impact on the three different types of switching (stimulus location, task, response). The variable is switch-cost efficiency, which assesses the difference between switched trials and repeated trials. A main effect of foreknowledge condition would indicate that foreknowledge does affect switch costs, addressing our first question. The Tukey's HSD test would then explore our second question, whether all partial foreknowledge conditions were equivalent or different in their effect on switch costs. Finally, interactions between foreknowledge condition and switching dimension - i.e. whether the switch involved the stimulus, the task or the response - would address our third question, whether switch-cost benefits from foreknowledge were specific to the trial property about which foreknowledge was given, or generalized to all dimensions.

There were significant main effects of switching dimension ( $F(2261) = 5.27, p = 0.0057$ ) and foreknowledge condition ( $F(4261) = 7.9, p < 0.0001$ ), but not of saccade type ( $F(1261) = 1.07, p = 0.30$ ). A key finding was that no interaction reached significance. For switching dimension, Tukey's HSD test showed that task-switch costs were higher than either stimulus-switch costs ( $F(1261) = 12.72, p < 0.001$ ) or response-switch costs ( $F(1261) = 16.96, p < 0.001$ ). For foreknowledge condition, Tukey's HSD test showed differences: (a) between no-foreknowledge and either response-foreknowledge ( $F(1261) = 12.91, p < 0.001$ ) or complete-foreknowledge ( $F(1261) = 21.10, p < 0.001$ ), (b) between stimulus-location-foreknowledge and task-foreknowledge ( $F(1261) = 7.86, p = 0.006$ ), response-foreknowledge ( $F(1261) = 23.04, p < 0.001$ ), or complete-foreknowledge ( $F(1261) = 33.65, p < 0.001$ ) and (c) between task-foreknowledge and complete-foreknowledge ( $F(1261) = 8.97, p = 0.003$ ) (Fig. 2). These results are quite similar to those on overall saccadic efficiency.



**Fig. 1.** Foreknowledge effects on saccadic efficiency. Stimulus foreknowledge has no effect on saccadic efficiency, task foreknowledge has some effect and response-foreknowledge is as effective as complete foreknowledge. Saccadic efficiency is a combined score of saccadic latency divided by one minus the error rate, both are shown below separately for prosaccades and antisaccades. Bars indicate group mean values of subject means and error bars represent the group standard error. Horizontal bars indicate statistically significant difference. NF = no foreknowledge, SF = stimulus foreknowledge, TF = task foreknowledge, RF = response foreknowledge, CF = complete foreknowledge.

Our analysis of switch costs was also directed at a specific question, whether foreknowledge for a specific dimension would selectively reduce switch costs for switches involving that dimension. The fact that there was no significant interaction between switching dimension and foreknowledge condition suggests that this is not the case. To address this further we performed separate *a priori* general linear models for each type of switch cost, with main factor



**Fig. 2.** Foreknowledge effects on switching costs. The upper graph shows the inverse efficiency-switch costs for the five foreknowledge conditions. Task-switch costs, stimulus-switch costs and response-switch costs are shown. Foreknowledge leads to reduced switch costs, in a pattern similar to saccadic efficiency. Partial foreknowledge effects were not specific for switching of the trial attribute for which foreknowledge was available. Horizontal bars indicate statistically significant difference. The lower panels show the latency and error rate components of the inverse efficiency-switch costs separately. NF = no foreknowledge, SF = stimulus foreknowledge, TF = task foreknowledge, RF = response foreknowledge, CF = complete foreknowledge.

of foreknowledge condition and subject as a random effect, followed by Tukey's HSD test to determine the effects of different types of foreknowledge on that particular switch cost. We collapsed across both prosaccades and antisaccades, given the lack of main effects or interactions found in the first analysis of switch costs. We also performed *a priori* linear contrasts to determine if there was a significant difference between no-foreknowledge and foreknowledge specifically for the dimension being switched.

*a) Stimulus-switch costs:* There was a significant main effect of foreknowledge condition ( $F(4,36) = 5.63, p = 0.0013$ ). Tukey's HSD test showed significant differences between complete-foreknowledge and no-foreknowledge ( $F(1,36) = 8.90, p = 0.005$ ), and between stimulus-location-foreknowledge and response-foreknowledge ( $F(1,36) = 10.70, p = 0.002$ ), task-foreknowledge ( $F(1,36) = 9.69, p = 0.004$ ) or complete-foreknowledge ( $F(1,36) = 12.92, p < 0.001$ ). Of note, there was no difference between no-foreknowledge and stimulus-location-foreknowledge (linear contrast,  $F(1,36) = 0.37, p = 0.54$ ).

*b) Task-switch costs:* There was a significant main effect of foreknowledge condition ( $F(4,36) = 6.04, p = 0.0008$ ). Tukey's HSD test showed significant differences between complete-foreknowledge and all foreknowledge conditions except response-foreknowledge ( $F(1,36) = 0.96, p = 0.33$ ). Of note, there was no significant difference between no-foreknowledge and task-foreknowledge (linear contrast,  $F(1,36) = 0.0222, p = 0.882$ ).

*c) Response-switch costs:* There was a trend toward significance for foreknowledge condition ( $F(4,36) = 2.1256, p = 0.0977$ ). Tukey's HSD test showed no significant differences. Of note, there was no significant difference between no-foreknowledge and response-foreknowledge ( $F(1,36) = 1.756, p = 0.193$ ).

To sum up, these results confirm a benefit of foreknowledge on switch costs, in keeping with the hypothesis that its optimizing effects may be particularly evident in reducing re-configuration costs on switched trials. The results also suggest, somewhat counter-intuitively, that foreknowledge does not reduce switch-costs in the specific dimension about which foreknowledge is provided. Rather, benefits appear to be general and to follow the pattern evi-

dent in overall saccadic efficiency. Complete foreknowledge reduces all types of switch costs to nearly zero (Fig. 2), response- and task-foreknowledge have some benefit on all switching – with the paradoxical exception that task-foreknowledge does not benefit task-switch costs – while stimulus-location-foreknowledge does not help with any type of switch cost.

#### 4. Discussion

Our results first confirm that complete foreknowledge about an upcoming trial increases saccadic efficiency, as a number of studies have previously demonstrated (Kingstone & Klein, 1993; Moschner & Zangemeister, 1993; Pare & Munoz, 1996; Schiller et al., 2004; Wegner & Fahle, 1999). Second, they show that partial foreknowledge about either stimulus location, task-set or response location do not have equivalent effects on saccadic efficiency. Stimulus-location-foreknowledge does not improve saccadic efficiency, response-foreknowledge is as effective as complete foreknowledge and task foreknowledge imparts an intermediate benefit, with efficiency better than that with no-foreknowledge but not as good as that with complete foreknowledge. Third, we examined switch costs, to determine if the processes involved in re-configuration of trial demands would benefit from foreknowledge. We found general effects that roughly paralleled those on saccadic efficiency. Of note, knowledge about an upcoming switch in a specific dimension (e.g. task) did not reduce the switch cost for that specific dimension any more than it did for switches in the other dimensions. All told, our results show that not all types of foreknowledge can be used to optimize behavioural efficiency.

#### 5. Partial foreknowledge and saccadic efficiency

Compared to complete foreknowledge, fewer studies have examined the effects of partial foreknowledge, and none have directly contrasted different forms of partial foreknowledge. The one most similar study of which we are aware also studied prosaccades and antisaccades under conditions of response-foreknowledge, stimulus-location-foreknowledge, complete foreknowledge and no-foreknowledge (Evdokimidis, Constantinidis, Liakopoulos, & Papageorgiou, 1996). However, it is not clear whether their response-foreknowledge condition corresponds to response-foreknowledge or task foreknowledge in our taxonomy (although we suspect the latter). Also, because their study focused on explaining the relative latency difference between prosaccades and antisaccades, their analysis did not examine the effects of foreknowledge condition on the error rate or latency of each saccade type. Hence the questions that we wished to answer cannot be addressed from their data.

A number of other studies, however, have data relevant to one or another of the types of partial foreknowledge in our report. For task foreknowledge, several studies have reported that task foreknowledge enhances saccadic performance in either error rate or latency (Barton et al., 2006a; Hsieh & Chen, 2007; Monsell, Sumner, & Waters, 2003; Ruthruff, Remington, & Johnston, 2001; Sohn & Anderson, 2003; Sohn & Carlson, 2000). Some have suggested that this benefit depends on the degree of certainty, with "unreliable" task foreknowledge – i.e. prior probability less than 1 – creating less benefit than reliable foreknowledge (Dreisbach et al., 2002; Kleinsorge & Gajewski, 2008). For stimulus-location-foreknowledge there are few relevant data. Some studies have reported that increased stimulus predictability reduces response latencies for prosaccades and antisaccades (Carpenter & Williams, 1995; Dorris & Munoz, 1998; Koval, Ford, & Everling, 2004), but since in these experiments the task was constant (prosaccade or antisaccade), these prior probability studies are more relevant to

our complete-foreknowledge condition. For the somewhat unusual response-foreknowledge condition, where the subject knows which direction the saccade will take, but not the combination of stimulus and task that will generate that response, we are not aware of any prior studies.

The fact that response-foreknowledge provides a significant enhancement of saccadic efficiency that is essentially equivalent to that seen with complete foreknowledge is perhaps not surprising. It may be that in both of these situations the subject is able to prepare a directionally specific motor response in advance. That is, all a subject may need to know is that a rightward saccade is the correct response, regardless of whether it is a prosaccade or an antisaccade. The stimulus/cue onset then merely triggers the execution of this 'pre-set' motor response without requiring computations regarding stimulus location and task set selection. In such a scenario, one might regard the resulting saccade as a 'substituted' response that bypasses the usual stimulus and task processing involved in making a saccade to a target.

The contrast between stimulus-location-foreknowledge and task-foreknowledge is of greater interest. In neither of these situations can a single directionally specific motor response be created in advance, since it cannot be known until the stimulus appears in which direction the saccade must be made. Despite the fact that both of these foreknowledge conditions reduce the set of behavioural options to two, only task-foreknowledge shows benefit compared to no-foreknowledge. Furthermore, the pairwise contrasts confirm that saccadic efficiency is superior with task-foreknowledge than with stimulus-location-foreknowledge. Thus, knowing whether one is to perform an antisaccade or a prosaccade is better than knowing whether the stimulus will be on the left or the right.

The lack of benefit from stimulus-location-foreknowledge in our paradigm has several possible explanations. First, if one conceives of the transformation from stimulus via task set to response as a simple cognitive model of sequential feedforward stages, then theoretically it should be possible to shorten processing time and enhance efficiency by pre-programming information in any of these three stages in advance of trial onset. On this basis our results suggest that stimulus processing is impermeable to foreknowledge. Indeed, this would be consistent with the conclusions of a study of priming of stimulus-related processes in task switching, that because of their automatic nature stimulus-driven processes are less likely to reflect internal factors like prediction than other cognitive processes like executive control (Sohn & Anderson, 2003). Another way of viewing this is that the efficiency of stimulus processing may be optimal already, limiting further improvement by foreknowledge.

A second, somewhat related possibility is that stimulus appearance in our paradigm serves two purposes, one being to indicate the location of the target, and the other being an initiation signal for saccadic execution. If the computation of location is at least as efficient as that for the initiation process, then there will be no benefit from improving the former, as the latter will then assume the role of the rate-limiting process.

A third possibility may be that the stimulus and task are not programmed in serial. While response preparation needs to be performed after stimulus localization, this is not necessarily true of task selection. Since the task cue and the stimulus occur simultaneously in our design, it may be that both task selection and stimulus localization occur in parallel. If task selection is the more demanding process, then any foreknowledge benefits in stimulus processing will not be apparent in reaction times or efficiency.

From single cell recordings in monkeys while they perform saccadic eye movements, a considerable amount is known about the preparatory activity patterns in oculomotor structures. The superior colliculus for example is involved in visual target selection (Basso & Wurtz, 1998), saccade selection (Glimcher & Sparks,

1992) and saccade preparation (Dorris, Pare, & Munoz, 1997). Several motor responses may be prepared in advance (Dorris & Munoz, 1998) and expectancy about the prior probability for saccadic target alters activity levels at the corresponding visuotopic locations of the superior colliculus (Basso & Wurtz, 1998). On this basis it is not surprising that complete foreknowledge and response-foreknowledge speed up reaction time: both allow the preparation of a single oculomotor response, with presumably higher activity peaks and thus faster response times. In the task-foreknowledge condition, on the other hand, two motor responses are possible and both may be prepared in advance, thereby explaining the intermediate benefit. We speculate that for both the stimulus-location-foreknowledge condition and the no-foreknowledge condition no response preparation is possible. This might be due to the conflicting activity patterns of antisaccades and prosaccades, which appear unpredictably in these two conditions: Preparation of an antisaccade involves suppression of a reflexive prosaccade (Munoz & Everling, 2004) that conflicts with the preparation of a prosaccade, which requires activation rather than suppression.

## 6. Foreknowledge and switch costs

Our examination of switch costs was motivated by current models of task-switching (Meiran et al., 2000), which include both active re-configuration effects (Monsell et al., 2000; Rogers & Monsell, 1995) and passive inertia effects persisting from the prior trial (Allport et al., 1994). Active re-configuration is triggered by the appearance of the instructional cue. For task set, the latency switch costs are greatest when the cue-stimulus interval is short, and gradually reach a minimum value as this interval approaches 800 ms, suggesting that active re-configuration is completed by 800 ms after cue onset (Meiran et al., 2000). By having our cues simultaneous with our stimuli, our experimental design ensured that costs of active re-configuration would be included in measures of stimulus-to-response latencies of our data. We asked whether active re-configuration of various trial dimensions could specifically benefit from foreknowledge regarding that dimension. Our analyses suggest that the answer is No. Rather, benefits in switching efficiency parallel the benefits in general saccadic efficiency. When either response or complete foreknowledge led to more optimized saccadic responses, all switch costs were also reduced. In contrast, there were little or no benefits to switch costs from task or stimulus-location-foreknowledge.

The fact that task-foreknowledge does not improve task-switch costs is consistent with previous studies. It replicates a result in one of our prior saccade studies, showing that a predictable task sequence did not reduce task-switch costs in latency or error rate (Barton et al., 2006a), a result that we replicated with the Stroop test (Barton et al., 2006b), in which the task switches between stimulus dimensions, rather than the stimulus-response mappings involved in prosaccade/antisaccade studies. All of these results are in agreement with other studies that also do not find any reduction in the costs of task switching with task foreknowledge (Dreher, Koehlin, Ali, & Grafman, 2002; Koch, 2005; Lien, Schweickert, & Proctor, 2003; Sohn & Anderson, 2001; Sohn & Anderson, 2003; Sohn & Carlson, 2000; Tornay & Milan, 2001).

The chief conditions in which we observed consistent benefits in switch costs were the response-foreknowledge and complete-foreknowledge conditions. In these situations, switching costs were reduced to zero, and in fact were not significantly different from zero for the complete-foreknowledge condition. This again is understandable if these types of foreknowledge are used to substitute a pre-packaged directionally specific motor response that bypasses any computations related to task setting and stimulus localization, a strategy in which stimulus onset merely serves as

a trigger for the execution of the movement. It may be that active re-configuration is just another computation that is bypassed by this substitution strategy. If so, this coupled with the general lack of benefit seen with task or stimulus-location-foreknowledge implies that the computations underlying switching may be relatively impervious to foreknowledge.

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