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Contextual effects on cognitive control and BOLD activation in single versus mixed saccade tasks

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ABSTRACT

The context or trial history of a task influences response efficiency in mixed paradigms based on cognitive control demands for task set selection. In the current study, the impact of context on prosaccade and antisaccade trials in single and mixed tasks was investigated with BOLD fMRI. Prosaccades require a look towards a newly appearing target, while antisaccades require cognitive control for prepotent response inhibition and generation of a saccade to the opposite location. Results indicated slower prosaccade reaction times and more antisaccade errors for switched than repeated or single trials, and slower antisaccade reaction times for single than mixed trials. BOLD activation was greater for the mixed than the single context in frontal eye fields and precuneus, while switch trials had greater activation than repeat trials in posterior parietal and middle occipital cortex. Greater antisaccade activation was observed overall in saccade circuitry, although effects were evident primarily for the mixed task when considered separately. Finally, an interaction was observed in superior frontal cortex, precuneus, anterior cingulate, and thalamus with strong responses for antisaccade switch trials in the latter two regions. Altogether this response pattern demonstrated the sensitivity of cognitive control to changing task conditions, especially due to task switching costs. Such context-specific differences highlight the importance of trial history when assessing cognitive control.

1. Introduction

The context in which a task is performed influences response efficiency based on recent experience with particular stimuli or task rules. The contextual factors of paradigm design and trial history impact behavior on laboratory tasks: when participants perform a single trial type repeatedly or alternate between two mixed trial types, behavior reflects the additional cognitive costs of maintaining multiple trial types in working memory and switching between task rules/sets between trials (Kiesel et al., 2010; Meiran, 1996; Rogers & Monsell, 1995; Vandierendonck, Liefooghe, & Verbruggen, 2010; Wylie, Javitt, & Foxe, 2003). A task set is the collection of perceptual, cognitive, and motor processes necessary to perform the instructed response following a certain stimulus and must be reconfigured between trials of different types (Rogers & Monsell, 1995). Cognitive control facilitates implementation of the appropriate task set through multiple supervisory processes that identify relevant goals. During cognitive control paradigms across domains, brain activation is observed in frontal, parietal, and anterior cingulate cortices, as well as in task-specific circuitry (Badre, 2008; Botvinick, Braver, Barch, Carter, & Cohen, 2001; Hutton, 2008; Miller & Cohen, 2001).

One model for investigating cognitive control is the ocular motor system underlying saccade production – a basic prosaccade (rapid eye movement towards a newly appearing peripheral stimulus) contrasts with a complex antisaccade (a movement away from the stimulus to the mirror image location, Hallett, 1978). Antisaccades necessitate the recruitment of greater cognitive control to suppress a prepotent response towards the target, invert the visual-motor spatial vector, and volitionally generate a saccade to an unmarked location (Hutton, 2008; McDowell, Dyckman, Austin, & Clementz, 2008; Munoz & Everling, 2004). Saccade tasks have been thoroughly studied in previous literature and antisaccade trials typically result in more directional errors, slower correct reaction times (RTs), and stronger BOLD fMRI (blood oxygenation level dependent functional magnetic resonance imaging) activation in saccade brain circuitry than prosaccade trials (Brown, Vilis, & Everling, 2007; Curtis & D'Esposito, 2003; DeSouza, Menon, & Everling, 2003; Ettinger et al., 2008; Ford, Goltz, Brown, & Everling, 2005; McDowell et al., 2008; Munoz & Everling, 2004; Noorani & Carpenter, 2013; Pierce, McCardel, & McDowell, 2015; Weiler & Heath, 2012).

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Previous studies of saccade tasks presented in different contexts reported both behavioral and BOLD activation differences. Ethridge, Brahmbhatt, Gao, McDowell, and Clementz (2009) compared behavior on prosaccade and antisaccade trials using separate single blocks or mixed task blocks. They found that in the single task condition saccade responses were faster and yielded fewer errors than in the mixed conditions (Ethridge et al., 2009). The context of separate trial performance facilitated the active saccade task set while the mixed context required frequent switching of task sets leading to weaker task representations of both saccade types. In Dyckman, Camchong, Clementz, and McDowell (2007), participants performed saccades in two different contexts in the fMRI environment: single tasks (blocks of only prosaccade or antisaccade trials versus fixation) or mixed task (alternation between blocks of prosaccade and antisaccade trials). The single task context showed significantly greater activation for antisaccades compared with prosaccades in typical saccade circuitry including cuneus, posterior parietal cortex (PPC), and frontal and supplementary eye fields (FEF/SEF; for reviews of saccade circuitry see Jamadar, Fielding, & Egan, 2013; McDowell et al., 2008), as well as in prefrontal cortex (PFC). The mixed context, however, only resulted in antisaccade-specific increases in the FEF, SEF and precuneus, suggesting that activation in other regions such as PFC was sustained across both tasks in order to maintain and switch between the two task sets (Dyckman et al., 2007). The current study also compared single versus mixed task contexts, but utilized an event-related design that pseudo-randomly interleaved saccade trials and fixation periods to minimize predictability of task order and allow separation of correct responses to various trial conditions.

This type of mixed context with multiple interleaved trial types requires switching between task sets and, therefore, reconfiguration of stimulus-response mappings and/or suppression of previous trial information (Meiran, 1996; Wylie & Allport, 2000). Task switching studies using various behavioral paradigms (Dove, Pollmann, Schubert, Wiggins, & von Cramon, 2000; Kimberg, Aguirre, & D'Esposito, 2000; Muhle-Karbe, De Baene, & Brass, 2014; Smith, Taylor, Brammer, & Rubia, 2004; Sylvester et al., 2003; Yeung, Nystrom, Aronson, & Cohen, 2006) reported greater activation on switched trials relative to repeated trials in regions including ACC, dorsolateral PFC, and PPC. This activation may support a general cognitive control or attention network during switching, although some findings indicated that these effects were not due to active task switching *per se* but to maintenance of, or competition among, multiple task sets (Brass & von Cramon, 2002; Gruber, Karch, Schlueter, Falkai, & Goschke, 2006; Ruge, Jamadar, Zimmermann, & Karayanidis, 2013). The use of a mixed task context in the present study may provide insight into this debate by investigating not only how activation for task switch and repetition trials differ, but also how the mixed context activation compares to the single task context where only one task set must be implemented (Cherkasova, Manoach, Intriligator, & Barton, 2002; Ethridge et al., 2009).

The current saccade paradigm includes another important factor beyond typical task switching studies: asymmetric task sets for prosaccade and antisaccade trials (Cherkasova et al., 2002). The simple, dominant prosaccade requires a habitual, stimulus-driven response, while the complex antisaccade stands in direct opposition to this potent tendency; therefore, additional activation increases for antisaccade task switch trials could demonstrate the engagement of control processes beyond that required for the inherent task set competition involved in a repeated antisaccade. One pair of studies previously evaluated trial history/task switching effects on mixed saccade tasks (Lee, Hamalainen, Dyckman, Barton, & Manoach, 2011; Manoach et al., 2007). They found differential activation in FEF and SEF following a previous antisaccade trial, as well as transient signal changes in FEF and anterior cingulate cortex (ACC) following a task switch. These studies, however, did not consider the difference between saccade trials performed in a mixed task context versus single task contexts with lower overall demands on task set selection, attention, and working memory.

In the current study, participants performed both single prosaccade or antisaccade tasks and a mixed prosaccade/antisaccade task to assess mixed task costs [single vs. mixed contexts; (Cherkasova et al., 2002; Dyckman et al., 2007)] as well as task switching costs [repeated trials vs. switched trials within the mixed context; (Manoach et al., 2007)] on saccade behavior and brain activation. Typical antisaccade costs (slower RTs, more errors, greater activation) were expected to be stronger in the single task contexts because increased working memory demands in the mixed task could make prosaccade responses less reflexive and more controlled, like antisaccade trials (Roberts, Hager, & Heron, 1994). Further, it was hypothesized that the mixed context and, in particular, task switch trials within the mixed context, would create the greatest demand on cognitive control of task set selection, resulting in behavioral costs (slower RTs, more errors) and increased brain activation in saccade and cognitive control circuitry. These comparisons reveal differences in how cognitive control is implemented for simple and complex visual-motor responses based on trial type and presentation context.

2. Methods

2.1. Participants

Sixty-five undergraduate students were recruited from the UGA Psychology Department online research pool and given course credit for their participation. Thirty individuals fulfilled exclusion criteria or voluntarily opted out before completing the study. Thus, data are reported from 35 right-handed, neurologically healthy participants (mean age = 19.5 years, SD = 3.5; 11 males), who experienced no current major psychiatric disorders or substance abuse, had no metal implants, and had normal or corrected-to-normal vision (via self-report). All participants provided written informed consent and activities were approved by the Institutional Review Board of the University of Georgia.

2.2. Task design

Participants completed saccade trials in two rapid event-related contexts: separate, single tasks of either prosaccade or antisaccade trials and a mixed task with interleaved prosaccade and antisaccade trials. The order of the tasks was counterbalanced across subjects. The single tasks consisted of one run of 60 prosaccade trials or 60 antisaccade trials, while the mixed task consisted of one run of 30 prosaccade and 30 antisaccade trials presented in pseudo-random order. Only the first 30 trials from the single task block were utilized in the analyses to minimize differences due to unequal trial numbers across contexts. Fixation periods between trials consisted of a central cross that appeared for 2000 to 8000 ms (average 3500 ms). For saccade trials, the trial type cue was illuminated around the cross for 500 ms (for prosaccades, a square; for antisaccades, a diamond). This was followed by a blank screen for 200 ms ("gap" presentation) and finally the peripheral stimulus (circle) appeared at +/−5 or 10° for 800 ms. All stimuli consisted of a 1° gray shape presented on a black background. Two peripheral stimulus eccentricities were included to reduce the likelihood of participants' anticipating the response location and preparing a specific motor response in advance (data collapsed across amplitude for analyses).