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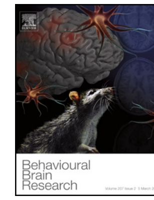

Research report

Reaction time-related activity reflecting periodic, task-specific cognitive control

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HIGHLIGHTS

- RT-related BOLD activity can reflect periodic engagement of cognitive processes.
- RT-related BOLD activity depends on task-specific demands.
- Periodic engagement is particularly evident during less-demanding tasks.

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ABSTRACT

Reaction time (RT) is associated with increased amplitude of the Blood Oxygen-Level Dependent (BOLD) response in cognitive control regions. The current study examined whether the Primary Condition (PC) effect and RT-BOLD effect both reflect the same cognitive control processes. In addition, RT-BOLD effects were examined in two Go/No-go tasks with different demands to determine whether RT-related activity is task-dependent, reflecting the recruitment of task-specific cognitive processes. Data simulations showed that RT-related activity could be distinguished from that of the primary condition if it is mean-centered. In that case, RT-related activity reflects periodically-engaged processes rather than "time-on-task" (ToT). RT-related activity was mostly distinct from that of the primary Go contrast, particularly for the perceptual decision task. Therefore, RT effects can reflect additional cognitive processes that are not captured by the PC contrast consistent with a periodic-engagement account. RT-BOLD effects occurred in a separate set of regions for the two tasks. For the task requiring a perceptual decision, RT-related activity occurred within occipital and posterior parietal regions supporting visual attention. For the task requiring a working memory decision, RT-related activity occurred within fronto-parietal regions supporting the maintenance and retrieval of task representations. The findings suggest that RT-related activity reflects task-specific processes that are periodically-engaged, particularly during less demanding tasks.

1. Introduction

Previous studies have found that BOLD amplitude increases linearly with RTs in cognitive control regions [21,3,9,16,18,14]. Although RT-related activity has now been found across different task designs [21], it is still not clear what cognitive processes it reflects. One influential account attributed RT-related activity to ToT or the amount of time that a region is active on any given trial [8,9]. This interpretation was based on findings that RT-related increases in the amplitude and the shape of the BOLD response are dependent and not separable. As stated by Grinband et al. [9], "...recent data have suggested that the duration of a subject's decision process, or time on task, can have large effects on the size of the elicited hemodynamic response, independent of the nature of the decision [8]." This account suggests that RT-related activity reflects the amount of time that underlying neural computations take to perform the decision process. On fast RT trials, this is relatively brief; while on slow RT trials it is relatively long.

Modeling RT-effects involves the creation of condition regressors for all conditions present, and separate RT-regressors for those conditions requiring a response. The PC regressor and its RT regressor share the same stimulus onset times, but differ in the amplitude

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(or in some cases, the duration) of the hemodynamic response function. The PC regressor has a constant amplitude, while the RT regressor amplitude is scaled by the RT on each trial. The RT regressor is generally orthogonalized with respect to the PC regressor. Even without orthogonalization, the RT regressor reflects additional variance not accounted for by the PC regressor. Despite this, many studies have found that RT effects occur across most of the same regions as the PC effect [21,18].

Such co-occurring PC and RT effects may be necessitated by the ToT account. According to ToT, RT-related activity reflects process time. Therefore, it always results in BOLD increases from baseline, which produces both significant RT, as well as significant PC, effects. However, RT-BOLD effects could occur in the absence of a PC effect. This scenario would only happen if the actual RT-activity in a region is suppressed on some trials (e.g., fast RT trials) and is positively active on other trials (e.g., slow RT trials). In this case, RT-related stimulus-evoked activity would still be linearly related to RTs, consistent with previous findings in the literature, but would be mean-centered instead of always positive. This type of RT-related activity, which results in a significant RT effect but not a PC effect, may reflect periodic-engagement of task processes rather than the length of the process time.

The current study examined RT-BOLD effects using two Go/No-go tasks with differing demands. The Simple task required a perceptual decision (green = Go, red = No-go), while the Repeat task required working memory to guide the decision (color switch = Go, color repeat = No-go). The aim was to determine whether the same regions show significant effects of both the primary Go and the RT contrast in each task, supporting a ToT account; or whether the two contrasts are non-overlapping, supporting a periodic-engagement account. RT-BOLD effects were also compared for the two tasks to determine whether they reflect task-specific cognitive control.

2. Materials and methods

2.1. Participants

22 healthy, right-handed adults (10 males), aged 20–40 years (mean = 28.97, SD = 5.22) participated in the study. Participants were recruited through local advertisements and had no history of mental illness or substance abuse. The study was approved by the Johns Hopkins Medicine Institutional Review Board. Informed consent was signed before task participation.

2.2. fMRI behavioral paradigm

Two Go/No-go tasks [1] were performed by all participants. For each trial, spaceship stimuli were presented for 300 ms followed by a 1500 ms inter-stimulus interval. 10 s blocks of rest occurred at the beginning, end, and four times throughout each run. Separation of hemodynamic events was achieved through the use of a trial epoch (1.8 s) that was not a multiple of the TR (2.5 s) and through the use of the occasional rest blocks. The use of incoherent trial and TR epochs is an effective alternative to jittering the interval between trials and allows the BOLD response to be sampled at different intervals from trial onset for each trial [11].

The proportion of Go:No-go trials was 3:1, with 78 Go trials and 26 No-go trials occurring in each run. Participants performed two runs each of the two Go/No-go tasks. Each run was preceded by instructions and 20 practice trials. Half of the participants performed the two Simple runs first and the other half performed the two Repeat runs first.

For the Simple task paradigm, stimulus-response associations were well-ingrained and easy to remember. Go stimuli were green while No-go stimuli were red. For the Repeat task, a more complex task rule that required working memory was used. Participants were required to remember the color of the previous stimulus. A change in the stimulus color signaled a Go trial, while a repetition of the stimulus color signaled a No-go trial. For this task, 50% of stimuli were blue and 50% of stimuli were yellow.

2.3. fMRI acquisition and preprocessing

Imaging data were acquired on a Philips 3T scanner. This included a high-resolution anatomical scan (MPRAGE, 8-channel head coil, TR = 7.99 milliseconds, TE = 3.76 ms, Flip angle = 8°). The behavioral task was performed during four fMRI runs (2D SENSE EPI, 8-channel head coil, TR = 2500 ms, TE = 30 ms, Flip angle = 70°). Each run was 4 min and 5 s in duration.

Preprocessing of functional data was performed using SPM8 and included: slice timing correction, motion correction, co-registration of the first functional image in the run to the MPRAGE image, segmentation of gray matter, white matter and cerebrospinal fluid using SPM probabilistic tissue priors, normalization to standard MNI space, resampling of voxels to 2 mm^3, and 8 mm full-width-at-half-maximum spatial smoothing.

2.4. fMRI data analysis

2.4.1. Go and RT data simulation

Before examination of the Go and RT-related activity, data simulations were performed to determine whether RT-related activity that is mean-centered (i.e., activity consistent with the periodic engagement account) produces a different pattern of results than RT-related activity that is positive linear (i.e., activity consistent with the ToT account). Time-courses were created to simulate data for five scenarios: 1. Go activity in the absence of a linear RT effect, 2. Linear RT-related activity centered around 0 in the absence of Go activity, 3. Positive linear RT-related activity in the absence of Go activity, 4. Go activity and linear RT-related activity centered around 0, and 5. Go activity and positive linear RT-related activity. Table 1 lists these scenarios and the type of cognitive process that each reflects. RT-related activity was simulated using both a zero-mean centered RT-regressor and a positive RT-regressor, in which RT-scaling on each trial was always greater than zero. This was done in order to determine whether the GLM model could separate Go and RT-related activity in both cases.

Data simulations for the five scenarios were derived from the actual SPM GLM regressors (see the following section, 2.4.2 Go RT Analysis, for details) for the 22 subjects. For the RT regressors, the RT values for each block were standardized by subtracting the mean and dividing by the standard deviation. This created a 0-mean centered regressor with standardized values for each block. For those simulations examining a positive RT effect, the absolute value of the minimum standardized RT value was added to all standardized RT values, thereby creating an RT time-course in which activity for the minimum RT trial was near 0 and activity positively increased with RT on all other trials. Activity for this positive RT simulation was never negative, whereas activity for the 0-mean RT simulation was negative for trials with RT less than the mean and positive for trials with RT greater than the mean. The data simulations were initially sampled at SPM's "micro-time", or the time-scale that is used to create the SPM model regressors, in which a time point occurs 16 times per TR (2.5/16 = 0.15625 s). The Go and RT-scaled events were convolved with the canonical HRF. To simulate data in which Go and RT-related activity occurred in the same voxel time-course, the Go and RT micro-time regressors were summed. For all simulated data, Gaussian random noise (mean = 0, SD = 0.1) was added to every time-point. The time-courses were then down-sampled to the TR resolution (every 2.5 s). The effects of Go, RT, and RT-Go for both the Simple and Repeat tasks were tested using the actual SPM