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Component processes in task switching: cue switch costs are dependent on a mixed block of trials

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ABSTRACT
People are slower when shifting than repeating tasks (switch cost). A considerable portion of the switch cost is due to the possibility of a shift in a mixed block where switches are possible (mixing cost), and to processing a cue that signals a task change (cue switch cost). We use an online sample ($n = 12,533$) and double cuing paradigm to examine the independent and interactive effects of cue switch costs and mixing costs. All effects were significant, with medium effects for cue changes ($\eta_p^2 = 0.06$) and task changes ($\eta_p^2 = 0.10$), a large effect for block context ($\eta_p^2 = 0.37$), and a small block by cue interaction ($\eta_p^2 = 0.04$) indicating that the role of the cue depends on the possibility of a switch. These findings offer empirical completeness by measuring the cue change in both blocks of a switching paradigm. The integrative approach quantifies how separable empirical components contribute to the overall switch cost.

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KEYWORDS
Task switching; cue switch cost; mixing cost; local switch cost; global switch cost

Introduction

The mental control of human actions is a central issue in cognitive psychology. A key theme in studying how actions is controlled is flexibility—being able to select and perform the relevant action among possible alternative actions, and to ignore competing actions or distracting information. As everyday life involves constantly changing environments, the ability to flexibly shift between actions (termed task switching) is crucial for the control of human behaviour. Task switching produces adaptable behaviour, but at a cost. Individuals are slower to respond when a task change compared to when a task is repeated, termed a switch cost.

A considerable portion of the switch cost is due to processes other than switching itself, including processing an environmental trigger (a cue) which signals a task change and preparing for a switch. Both these supporting components have been widely supported, but not measured in conjunction with each other. By combining these empirical effects in light of each other, we examine the extent to which each component of the switch cost depends on other components.

Components of a switch cost

Task switch cost

Switch costs have been extensively studied using the task-switching paradigm (Jersild, 1927; Spector & Biederman, 1976). In a standard task-switching paradigm setup, participants complete blocks of trials in which only one task is performed (single task or non-switch blocks), followed by a block in which both tasks are performed (mixed or switch block). In the explicit cuing version of the paradigm, an external signal (cue) informs the participant which tasks to perform per trial. In the mixed block, the cost of switching can be measured as the difference in response times between transitions of trials in which a task changes (task switches) and transitions of trials in which a task repeats (non-switch or task repetitions). The task switch cost (also called local switch cost or specific

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switch cost) thus parses a task change from baseline processes required for speeded response time tasks that are not specific to switching (termed processing speed; Salthouse, 1996, 2005).

Mixing cost

In addition to the cost of a switch itself, participants are slower on task repetitions in a mixed block of trials compared to task repetitions in a pure block of trials (mixing cost, global switch cost, or general switch cost; Los, 1996). Mixing costs reflect the additional working memory load of having more tasks in a mixed block, and the increased readiness required to prepare for a possible task change even if a change does not occur (Braver et al., 2003; Los, 1996, 1999; Rogers & Monsell, 1995; Rubin & Meiran, 2005). Mixing costs tend to be larger than task switch costs, indicating that a notable proportion of the overall switch cost is due to the cost of being prepared to possibly switch. Dissociation studies using the task-switching paradigm show that mixing costs and task switch costs reflect separable components of the overall switch cost (Braver et al., 2003; Dreisbach et al., 2002; Meiran, 2000; Rogers & Monsell, 1995).

Cue switch cost

A key limitation of the standard paradigm is that each time a task changes in switch blocks, a cue also changes. Similarly, each time a task repeats, a cue repeats. The confounding of task and cue switches means the true cost of a task change cannot be separated from a cue change. A solution to the problem was proposed by a double cuing paradigm, which uses two cues per task (i.e. a 2:1 mapping of cue per task) instead of one cue per task in the standard paradigm (Logan & Bundesen, 2003; Mayr & Kliegl, 2003). The addition of two cues per task can be used to isolate the role of the cue, as it creates three trial transitions: where the cue and task repeat (non-switch trials or cue repetitions), where the cue changes and the task stays the same (cue switch trials or task repetitions), and where both the cue and task change (task switches).

The impact of a cue change (cue switch cost) can then be measured as the difference in response times between cue switches and task switches. Cue switch costs can be larger than task switch costs (Logan et al., 2007), indicating that a nontrivial proportion of the overall switch cost is due to processes related to using the cue to select a task. Cue switch costs reflect time for cue encoding, either via automatic priming using the cue, or an executive control process to load the current task into working memory (Logan & Bundesen, 2003; Mayr & Kliegl, 2003). Dissociation studies using the double cuing paradigm suggest that cue switch costs and task switch costs reflect separable empirical components of the overall switch cost (Altmann, 2006, 2007; Gade & Koch, 2007, 2008; Horoufchin et al., 2011; Koch et al., 2010; Mayr, 2006; Mayr & Kliegl, 2003; Monsell & Mizon, 2006, c.f., Logan & Bundesen, 2003, 2004; Arrington & Logan, 2004, 2005; Arrington et al., 2007).

Investigating cue switch costs with mixing costs

In the current study, we investigated how the effect of a cue change (cue switch cost) is influenced by the context of a mixed block of trials (mixing cost). Cue switch costs have been previously measured solely using trial transitions from a mixed block of trials. This measurement confounds cue-related processes with processes related to maintaining readiness for the possibility of a task switch in a mixed block. As the mixing cost literature shows, considerable time is given to the latter set of processes.

An alternate approach is to measure a cue change in a pure block of trials, without the context of a possibility of a switch. On one hand, it is possible that measuring a cue change alone in a single task block is a purer measure of a cue switch cost than measuring a cue change in a mixed block. On the other hand, it is possible that measuring a cue change alone is a qualitatively different measure, as the cue is not informative in a pure block. The latter case is more intuitive as processing a cue may be dependent on the usefulness of the cue in signalling a task change, such that a cue would only have an effect in a mixed block as this block includes the circumstance that a task change may occur. Hence it is plausible that the cue interacts with the mixing cost of preparing for the possibility of a task change. In the current study, we directly test this possibility, which has until now only been an implicit assumption in the task cuing literature.

Measuring if the cue change interacts with the block context is useful to test for completeness in the double-cuing paradigm measurements. Studies with the standard task-switching paradigm have indicated that the cue may be influenced by block context, such that the cue plays a role across trials in a mixed block rather than on switch trials only. The underlying process proposed to prepare for the possibility of a task switch in a mixed block has been found to rely on task cuing (Rubinstein et al., 2001). The information provided by a cue may be used across trials in a mixed block to efficiently achieve a state of readiness (Altmann & Grey, 2008). The cue is specifically useful as it provides context on how to respond in mixed blocks by linking a task cue to a semantic task category (Braver et al., 2009). This set of evidence on the role of the cue in a mixed block suggests the cue switch costs may be limited to mixed blocks.

Relatedly, the role of the cue has been found to vary depending on how informative or relevant a cue is for the context in which it occurs. Fully and partially informative cues (that specified an upcoming switch) were linked to a switch cost, while uninformative or invalid cues were not (Karayanidis et al., 2009; Ruthruff et al., 2001). In a similar vein, the subjective expectancy of a switch is influenced when cues are informative (the cues signal which task to switch to), but not when cues are partially informative (i.e. they provided information that a task would change or repeat, but not on which task type was needed when a task changed; Dreisbach et al., 2002). Switch costs did not vary with different switch probabilities, but response times were faster on both switch and non-switch trials if the cue indicated a task with high probability, indicating that the cue is used to inform responding in a non-switch-specific way. Further, cue switch costs, but not task switch costs, were eliminated with transparent cues (in which the cue clearly indicated the task-set representation needed for the task; Grange & Houghton, 2010). Large cue switch costs and task switch costs occurred with non-transparent cues (in which there was an abstract relationship between the task cues and task-set representation). Similarly, having cues that are more familiar, recent, transparent, or salient, reduces switch costs, and conversely, less familiar cues increases switch costs (Forrest et al., 2014; Gade & Koch, 2007; Schneider, 2016; Schneider & Logan, 2011).

Current study

Our paradigm contained three trial types and two types of trial blocks, producing five trial classifications in total (Figure 1). Pure blocks consisted of no task or cue changes (non-switch trials), along with cue-only changes (cue switch trials). Mixed blocks consisted of no cue or task changes (non-switch trials), cue-only changes (cue switch trials), or cue and task changes (task switch trials).

The resulting block, cue change, and task change manipulations produced a set of trial types that each reflect a different combination of components that contributes to an overall switch cost (Figure 2). We then subtracted the effect of each manipulation to fractionate the empirical components that produce a switch cost. Following this, we investigated interactions between manipulations to examine the nature of the control processes that may underlie the observed components.

The study setup also allowed the examination of the magnitude of cue switch costs, mixing costs, and task switch costs in a single experiment. We examined the effect sizes for each contributor to the total switch cost, allowing us to parse the overall switch cost into the relative magnitudes of contributing effects. A large number of participants in the current study was ideal for quantifying the magnitude of different components, as the sample size enables the estimation of precise estimates of these magnitudes.

Methods

Participants

The study was conducted online, via a task on the website of one of the authors (SR). Implementation was identical to Reimers and Maylor (2005). The majority of participants accessed the task by a prominent link on the BBC Science website, related to a TV series that involved the same author (similar in style to Reimers, 2007). Sessions were brief (<10 min), to encourage participation and task completion. The task was completed 29,242 times. Some completions were excluded (25 where participants who reported an age below 10; 12,629 with an error rate over 35% in at least one experimental condition, 1,346 with no age reported, and 485 were participants indicated that they had completed the task before). The final sample after exclusions consisted of 14,757 individuals (4139 identifications as male, 10,536 identifications as female, and 82 no response). The post-trimming final sample size was 12,533 (see Results).

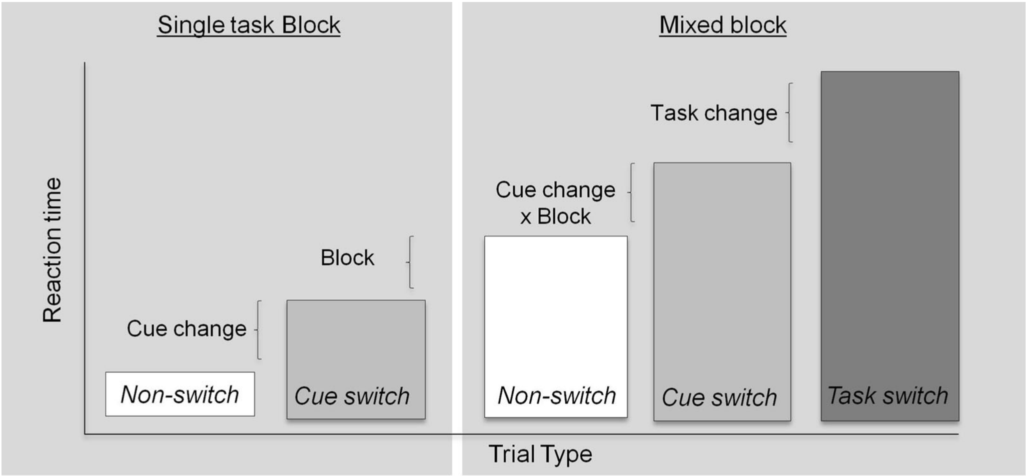

Figure 1. A schematic diagram of trial types for the combined paradigm arranged in order of complexity. The combined paradigm in the current study manipulated a cue change, block, and a task change. Each task manipulation leads to a further increase in response time. The image shows how trial types are subtracted to create components of a switch cost. Note: Image based on Jost et al. (2015, Figures 1C and 2C).

Participants included in the final sample had an age range of 10 to over 66 years[1], with a median age of 23 (*interquartile range* = 15). Age and gender were self-reported. Participants were given information about the task before commencing the study, so they knew what they were consenting to. Our obtained sample size was sufficient to detect an effect size of $\eta_p^2 = 0.001$, giving us power to detect even a tiny effect. For the smallest achieved effect size ($\eta_p^2 = 0.04$), with 5 measurements (trial types), we achieved a power of 1.0 for each analysis, as determined using the statistical software G*Power 3.1 (Faul et al., 2009).

Data from this sample were also used for another study (unpublished). The goal of the other study was to investigate age differences in task switching. Both studies have independent goals, and thus are reported separately.

Materials

The task-switching paradigm used in the current study was similar to Reimers and Maylor (2005). It consisted of two task sets with the addition of two cues per task ("emotion" or "feeling", and "gender" or "sex"). Two stimuli were used: either a happy female face and a sad male face, or a sad female face and a happy male face. The stimulus set was randomly allocated between subjects.

Design and procedure

The experiment consisted of three blocks: Two single-task blocks, and a mixed block. All tasks were choice reaction time measures, in which participants pressed a keyboard button ("D" or "K") to select one of two responses (happy/sad or male/female).

Key mappings were made at the start of the experiment, and they remained consistent across blocks. After key mappings were made, the two stimuli to be used were selected to create incongruent mappings of the two response options, so that the participant would have to give a different response to each stimulus depending on which task was cued. Key mappings were randomised for each participant.

The single task blocks consisted of 12 trials. The cue changed every two trials but was redundant in these blocks. In the single-task blocks, participants categorised each face according to gender (male/female) or emotion (happy/sad), with the order of single-task blocks randomised across participants. The two face stimuli were presented equal numbers of times in random order.

The switching block consisted of 50 trials (two filler trials at the start; 48 experimental trials). As in Reimers and Maylor (2005), trials were paired, with repetitions of the same cue, meaning that trials were always cue/task switch followed by non-switch, followed by cue/task switch followed by

[1]Participants reported their actual age, but individuals over 65 were grouped into a single age of "66+".

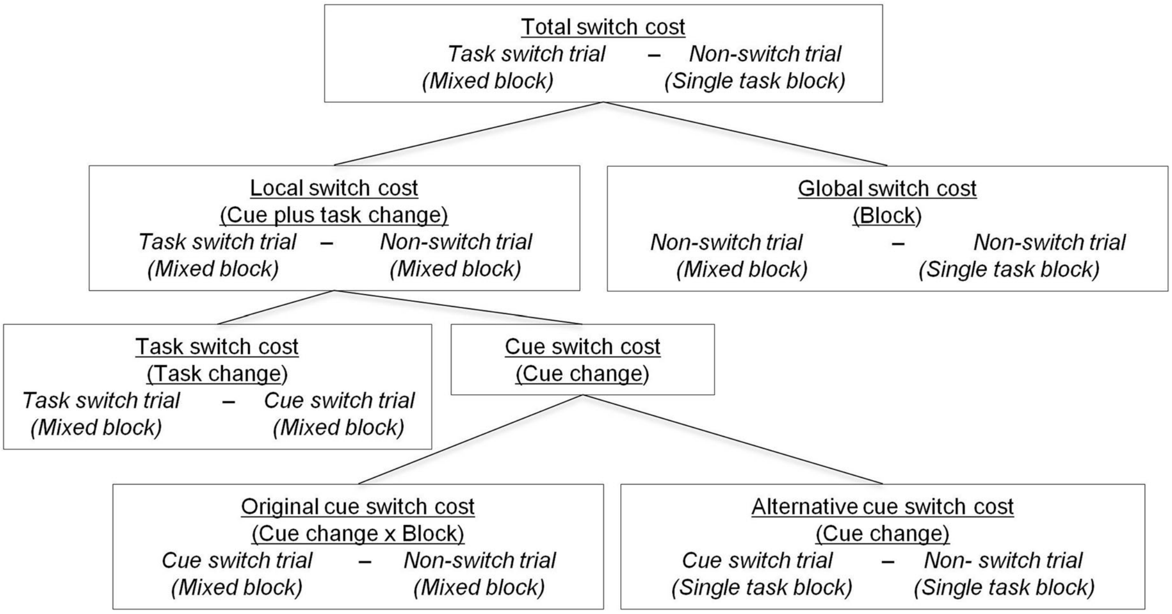

Figure 2. Components of the task switch cost, and calculations for each component. Note: Image adapted from Meiran et al. (2000, Figure 16).

non-switch. For example:

$$c_1t_1 - c_1t_1 - c_2t_1 - c_2t_1 - c_1t_1 - c_1t_1 - c_3t_2 - c_3t_2 - c_1t_1 - c_1t_1 - c_4t_2 - c_4t_2 - c_3t_2 - c_3t_2$$

NS CS NS CS NS TS NS TS NS TS NS CS NS

where c1 and c2 are separate cues for task t1 (i.e. Emotion, Feeling), and c3 and c4 are separate cues for the task t2 (i.e. Gender, Sex). Trial type indicated as non-switch (NS), cue-only switch (CS) and task switch (TS). Order of switches (CS or TS) was randomised subject to the constraint that there were exactly 12 cue-switch trials and 12 task-switch trials (as well as 24 non-switch trials), and no more than three consecutive switches of the same type.

The sequence of stimuli was constrained so that one of the two face stimuli was chosen with a 50% probability for each trial. The exception was when the previous three stimuli were all the same face, in which case the other face was used.

At the start of a trial, a cue appeared which remained on the screen throughout the trial. After 250 ms[2], one of the two face stimuli for that participant was presented for 250 ms. As soon as the face was presented, participants could respond using the keyboard. Immediately after a response, the cue disappeared, and there was a 1500 ms inter-trial interval (ITI) before the next trial began. Following an incorrect response, a box with the word "OOPS!" Appeared on the screen for 1000ms, after which there was an ITI of 1,750 ms and the next trial started.

The paradigm had five trial types in total: two in the single-task block (non-switches and cue-only switches) and three in the mixed block (non-switches[3], cue-only switches, and cue plus task switches). Reaction times and percent error were measured for each trial type. Incorrect responses and reaction times under 200 ms were excluded from analysis. Data were collected between April 2006 and May 2011.

Analyses

Analysis of variance (ANOVA)

Trial types were classified into factors and examined using an ANOVA. Coding trials into factors allowed

[2]The times given here are those that were specified in the code. In practice, as the code has no control over monitor synchronization or other processes on the user's computer, they are likely to be imprecise. For a discussion of presentation duration accuracy under Adobe Flash, see Reimers and Stewart (2015).

[3]Technically, there were two types of non-switch trials in the switch block: non-switch after cue switch, and non-switch after cue plus task switches. Both fall under the broad category of non-switch trials. In calculating processes for switch cost, only one non-switch trial type was used (non-switch after cue plus task switches) to provide a purer baseline for process subtraction. However, analyses were also run on the second type of non-switch trials (non-switch after cue switch) and compared for differences. No significant change was observed when adding the additional trial type.

us to examine the different categorizations between trial types—for example, between trials in the same block (a main effect of the block), and between non-switch and cue switch trials (a main effect of a cue change).

Based on the literature for task switch and mixing costs, the factor of a task change was measured by comparing trials in the same block to measure the process for within-block or local switch cost. A between-block or mixing cost was measured using a factor of block to compare the non-switch trials in single task and mixed blocks. A task switch cost was measured using a factor of task change to compare task switch and cue switch trials in a mixed block. A cue switch cost was measured using a factor of cue change to compare cue switch trials to non-switch trials, in both single task and mixed blocks.

It is logically impossible with the current experimental design to have task-switch trials in a single task block, or to have a task change without a cue change (Figure 1). Due to the unbalanced design, a single ANOVA with all the manipulations for trial types does not produce a complete factorial design as all possible combinations of each level of each factor were not measured. Hence, trial types were classified into two separate ANOVAs. For the first ANOVA, trials between blocks were used to produce a 2×2 ANOVA (cue change: non-switch, cue switch; block: single task, mixed). For the second ANOVA, trials within a switch block were used to produce a one-way ANOVA (task change: cue switch, task switch).

To summarise the factors tested were as follows:

- block: single-task block versus mixed block
- task change: task-switch trials versus cue switch trials (in a mixed block)
- cue change: cue switch trials versus non-switch trials (in both blocks)

Effect sizes

We focus on interpreting effect sizes over statistical significance in our results, in line with recommendations to always discuss effect sizes in publications, more so than statistical significance (Flora, 2020; Ferguson, 2009; Wilkinson & APA Task Force on Statistical Inference, 1999). The use of effect sizes is particularly relevant to the current study because very large sample sizes yield low *p*-values regardless of theoretical or practical significance. As we found statistically significant differences for small effects, the interpretation of effect sizes provided a more accurate picture of the magnitude of the observed significant effects.

We report effect size in three ways. First, we report standardised effect sizes for each effect of interest in the ANOVA using partial eta-squared (η_p^2). Standardised effect sizes are interpreted according to published guidelines, of $\eta_p^2 = 0.01$ and above representing a small effect size, $\eta_p^2 = 0.06$ and above representing a medium effect size, and $\eta_p^2 = 0.14$ and above representing a large effect size (Cohen, 1992). Unstandardised effect size measures are used in addition to standardised measures, as published studies strongly recommend unstandardised effect sizes for being easier to interpret, more robust, and more versatile than standardised effect sizes (Baguley, 2009; Ferguson, 2009; Flora, 2020).

In addition, we report two measures of unstandardised effect size: the actual effect size (the difference scores for the increase in response times per experimental manipulation, measured using the units of the measurement instrument, in this case, response times in milliseconds), and the percentage increase in reaction time for each effect (American Psychological Association, 2006; Rubinstein et al., 2001). The percentage increase is calculated as

$$\%\text{increase} = (\text{increase}/\text{original value}) \times 100 \quad (1)$$

where,

$$\text{increase} = \text{new value} - \text{original value} \quad (2)$$

The numerator measures the increase, which is essentially the difference score between the new and original value. The denominator measures the original value, which is essentially the baseline reaction time without any manipulations. The new value is the reaction time after an experimental manipulation.

Difference scores are widely used to measure switch costs in cognitive psychology (Kiesel et al., 2010; Meiran, 2010; Monsell, 2003; Vandierendonck et al., 2010). The percentage increase complements difference scores as a way to practically and intuitively interpret the effect size of a switch cost. Published recommendations suggest interpreting unstandardised effect sizes based on the researchers' knowledge of what is a meaningful effect size, instead of using the arbitrary size classifications for standardised effect sizes (Cohen, 1992; Flora, 2020). To provide context for interpreting unstandardised reaction time effects, an effect size of tens of milliseconds in common in cognitive psychology reaction time studies, while an effect size of hundreds of milliseconds (as is typical in task switching research) is large and rare (Monsell & Driver, 2000).

Results

Analyses were conducted using the R language and environment for statistical computing. Before analysis, each participant's reaction times were trimmed using a recursive trimming script to remove data that were greater than 4 standard deviations above the mean for each condition (i.e. within-participant trimming by condition). An across-participant recursive trimming procedure was then applied, with the criterion changing as more participants were removed (technique described in Van Selst & Jolicoeur, 1994). Trimming was done per age per condition using the R package trimr (Grange, 2015). When an extreme reaction time was found, that subject was excluded from the sample. Means for each trial type are presented in Figure 3.

The 2 × 2 (block x cue change) between-blocks ANOVA revealed a significant main effect for block, $F(1, 100260) = 59{,}559$, $p < .0001$, with a large effect size, $\eta_p^2 = 0.37$, such that response times were longer in the mixed block than the single task blocks (MD = 293, SE = 1.20). The main effect of cue change was significant, $F(1, 100260) = 6863$, $p < .0001$, with a medium effect size, $\eta_p^2 = 0.06$, such that response times were longer for cue switch trials than non-switch trials across blocks (MD = 100, SE = 1.2). Finally, the interaction of block and cue change was significant, $F(1, 100260) = 3837$, $p < .0001$, with a small effect size, $\eta_p^2 = 0.04$. Tukey post-hoc tests revealed that response times were longer for cue switch trials than non-switch trials in both blocks, but with a larger difference in mixed blocks (MD = 174, SE = 1.7) than in single task blocks (MD = 25, SE = 1.7). The one-way within-blocks ANOVA revealed a main effect of task change, $F(1, 50130) = 5814$, $p < .0001$, with a medium effect size, $\eta_p^2 = 0.10$, such that response times were longer for task switch trials than for cue switch trials in the mixed block (MD = 183, SE = 1.6)[4]. Main effects and interactions of task type were also examined as a secondary analysis to test for asymmetric switch costs (comparing the easier gender classification task to the more difficult emotion classification task), and are presented in the Supplemental Material.

For unstandardised effect sizes, difference scores and percentage increases were then used to calculate each component of the switch cost. Baseline response times took 534.1 ms to complete. A cue change in a single task block (the alternative cue switch cost) lead to a small increase in the response time of 25.1 ms (5% longer). Block (mixing cost) lead to a large increase in the response time of 218.9 ms (41% longer). A cue change in a mixed block (original cue switch cost) lead to a further increase of 149.0 ms (28% longer). Finally, a task change in a mixed block (task switch cost) increased response times by 182.7 ms (34% longer). A graph dividing the total response time of a task switch trial into the effects of the different factors is presented in Figure 4.

Discussion

Task switching performance was partitioned into distinct components for a cue change (cue switch costs), a task change (task switch costs), and block context (mixing costs). Using a large sample collected online, we extended past findings of these effects by quantifying their relative contribution to the total switch cost. Medium to large cue and mixing switch costs were demonstrated even when a task change does not occur, and the mixing cost was considerably larger than the switch cost, highlighting that supporting processes are as important for successful shifting as shifting a task itself. Our novel integrative approach highlights that the extent to which individual components contribute to the overall switch cost can only be examined by investigating all components simultaneously.

We also found a novel interaction between cue switch costs and mixing costs, with a larger cue switch cost in mixed blocks than single-task

[4]Analyses were re-run after removing error trials as well as the trials following an error, as removing post-error trials accounts for the nature of the error being unknowable. The pattern of results was the same after excluding post-error trials, all p's <.0001. Effect sizes were also similar: The between-blocks ANOVA revealed a large effect for block η_p^2=0.33 (previously η_p^2=0.37), a small effect for cue change η_p^2=0.05 (previously η_p^2=0.06), and a small cue by block interaction η_p^2=0.04 (previously η_p^2=0.04), and the within-blocks ANOVA revealed a medium effect size for task change η_p^2=0.09 (previously η_p^2=0.10).

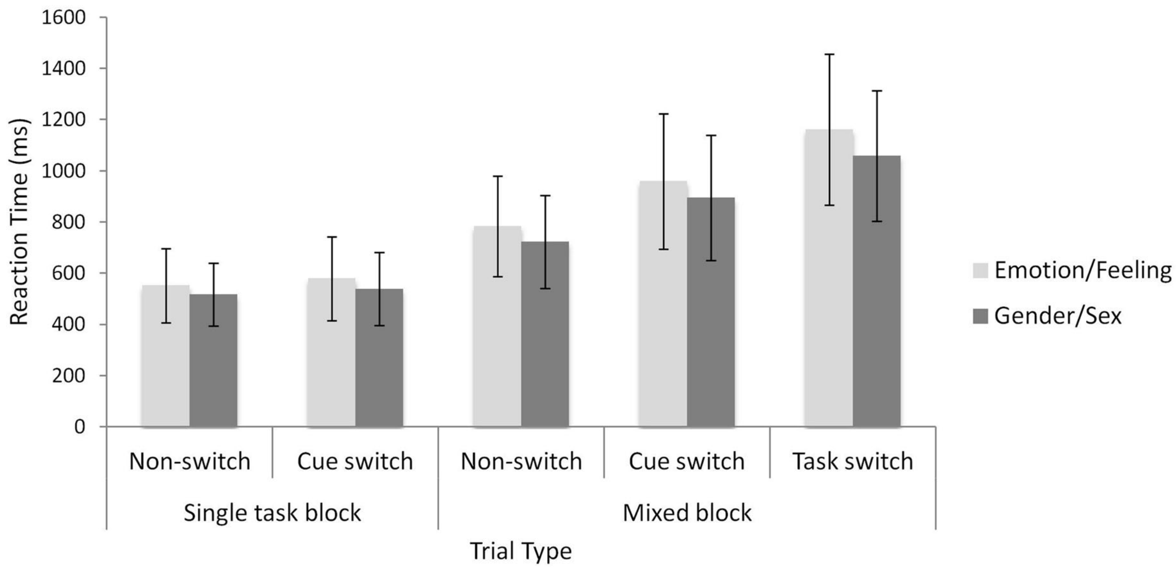

Figure 3. Means response times (+/— 1 SD) for each trial type, separated by task type. The response time for each trial type increased as the trials became more complex.

blocks. The observed interaction deconfounds the widely supported role of the cue from the widely supported (but separately investigated) role of block context. The interaction offers insight into the nature of the cue in a switching paradigm, by indicating that the role of the cue is specific to a context in which the task may change. The interaction thus confirms the inherent but untested assumption in the cue switching literature that the cue switch cost is dependent on the block context.

Parsing a cue switch cost

The double cuing paradigm has provided a unique means to isolate a cue change from a pure task change, as cue switch costs and task switch costs were confounded in the standard task switching paradigm. Findings from this paradigm show that a substantial portion of the cost of switching between tasks is due to the role of a cue that signals the task change (Logan & Bundesen, 2003; Mayr & Kliegl, 2003; Jost et al., 2015). We add to these findings to

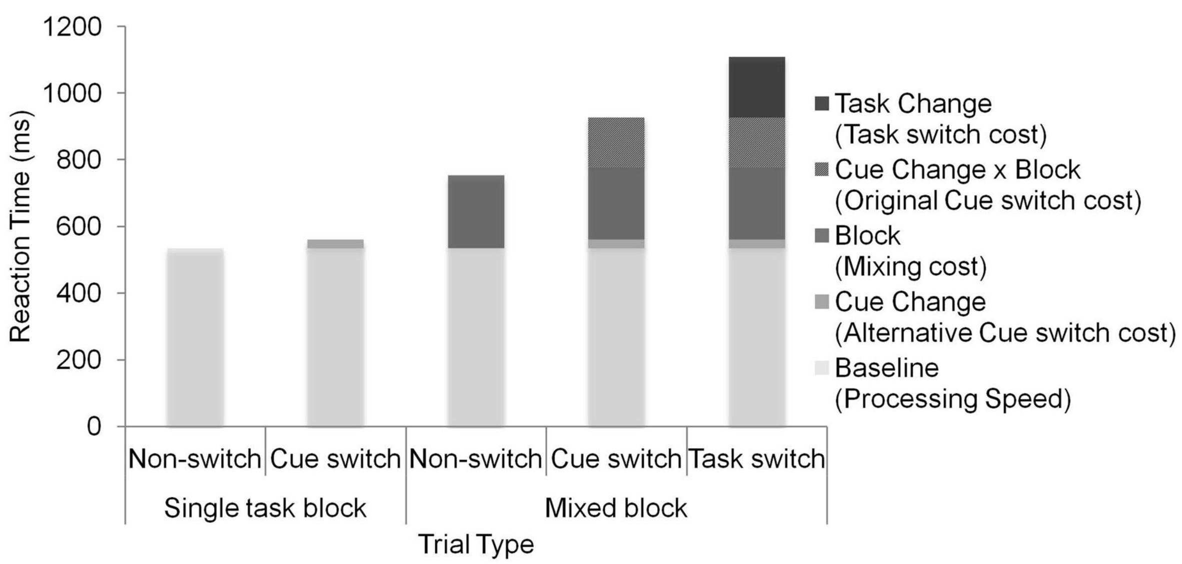

Figure 4. Mean response times (in ms) for each trial type. The response time for each trial is divided into the control processes for that trial. Control processes are explained by the factor (i.e. experimental manipulation) and the empirical component that is measured (in parentheses).

show that the role of the cue is dependent on the possibility of a task change, possibly as a cue has an effect only in circumstances where the cue can signal a potential task change. This finding explicitly tests what was previously only an implicit assumption in the task cuing literature—that the cue is used specifically to signal a new task.

Researchers have not explicitly clarified whether or not they expect a cue change to be influenced by block. We expect this oversight is built on the assumption that a cue change is only of interest in a mixed block—that is, under the context of a possible task switch. Intuitively, this makes sense. Without the possibility of a switch, the cue has no utility and may even be distracting. Participants may thus block out the cue, so one could expect smaller cue switch costs in single task blocks than in mixed blocks, due to processing the cue less frequently. However, the intuitive assumption that a cue change is not informative in a single task block had yet to be empirically demonstrated. If a cue change also had an effect in a single task block, then it could be used to calculate a purer measure of the cue switch cost which was not confounded by the presence of task switch trials.

Accounting for cue switches in a single task block is empirically useful, as it offers completeness in accounting for all the conditions in a double cuing paradigm. Studies that used the task switching paradigm have found an effect of switching a task within and between blocks, and have even shown that the between-block effect of a mixing cost is larger than the task switch cost. Yet studies that used the double cuing studies have been limited to the effect of switching a cue within a mixed block only.

Mixing costs have been widely replicated using the task-switching paradigm. Cue switch costs have also been widely replicated using the double cuing paradigm. A missing link was to measure the mixing and cue switch costs in a single experiment, which we did in the current study. We partitioned switch cost into a framework with all the previously demonstrated effects (Figure 2). Future studies should test this framework using experimental manipulations targeting the independence of each of the proposed components, and their underlying mechanisms.

Quantifying processes underlying a switch cost

Going by the standards of response time effects, the switch cost is extremely large (hundreds, instead of tens, of milliseconds; Monsell & Driver, 2000). The current study replicated the extremely large effect size of a switch cost. Further, we were able to quantify the time taken for the components that contribute to the overall switch cost, and to thus partition the total switch cost into each of the contributing effects.

At the broadest level, a switch cost can be measured at the difference between a non-switch trial in a mixed block and a switch trial in a single task block. The simple difference score conceivably measures the cost of switching by comparing trials in which a switch always occurs to trials in which a switch never occurs. Early investigations used this measurement, until it was discovered that the simple difference score confounded a number of factors into a single measurement, such as the effect of the possibility of a switch measured by a mixed block (mixing cost) and the signal for an upcoming switch measured by a cue change (cue switch cost). Such findings provided two major implications. One, the additional effects (mixing costs and cue switch costs) could be parsed out to create a purer measure of a task switch cost. Two, both of these measures had greater impacts on the total switch cost than the actual task change itself.

The current study contributes to past investigations by quantifying the processes that contribute to the switch cost, for the parameters used in the current study. The findings showed that it took 534 ms on average to perform a single task, indicating that baseline processing speed was around half of the total response time. The second-largest contributor was being ready for a potential task change (mixing cost), which took 219 ms (or 41%) longer. The large mixing cost indicates a substantial cost of increased readiness for a shift, even when a shift does not occur. It took 148 ms (or 28%) longer to use a cue to decide on the task to perform when anticipating a possible shift, although the cue only has a trivial effect of 25 ms (5%) longer when there is no possibility of a shift. Importantly, the effects of maintaining readiness (i.e. a mixed block context) and using a cue for a task decision (i.e. a cue change) occur even without an actual shift taking place, indicating the long-term impact of the possibility of a switch costs 74%. It took 183 ms (or 34%) longer for an actual shift. Thus, the magnitude for supporting processes was larger than the magnitude of the task change itself.

The sum of these effects is 576 ms (or 108%) longer. The substantial increase of 108 percent on top of the time for a single task highlights the sizable cost of switching. This finding implies that for simple tasks (such as the ones used in the current study), the total time for switching is longer than the time it takes to do that task in the first place. The task switching literature has consistently confirmed the existence of a switch cost, but less was known on the magnitude of such an effect, or the relative magnitude of contributing processes.

The reporting of percentage increase is relatively novel; It has only been done by one other study on task switching (Rubinstein et al., 2001). Percentage increase is useful in situating the impact of a switch cost, which can take around a hundred milliseconds (one tenth of a second), but accounts for a notable increase of up to 40% of the time for doing a single task (American Psychological Association, 2006). Percentage increases are especially easier to interpret by researchers who are not in cognitive psychology or unfamiliar with how to interpret absolute millisecond effects. Absolute millisecond effects can appear trivial on their own but are large when placed relative to the time it takes to complete a task in the first place. For example, the total cost of a shift is around five hundred milliseconds, or half a second, which seems brief. However, this translates to a 108% decrease in productivity, which is substantial.

The online data collection in the current study offered the opportunity to obtain a highly powered sample. Past studies have confirmed the reliability of online cognitive response time tasks compared to lab settings, and have unequivocally found that the increase in sample size offsets the decrease in control (Crump et al., 2013; Hilbig, 2016). Accurate estimates of response times have been found using Adobe Flash, the programme in which tasks for the current study were implemented (Reimers & Stewart, 2007, 2015). Task switching paradigms are particularly well-suited to web-based data collection, because features of task switching make it robust to potential web-based data collection issues, including features such as the within-subject response time comparisons and use of multiple trials (Reimers & Stewart, 2016).

A potential limitation is that a high number of participants were removed due to high error rates or outlier response times. Another limitation is that a low number of trials were used to calculate condition means. Low error rates, fewer response time outliers, and larger numbers of trials per condition are possible to obtain in online studies with simple experimental designs, such as having only two conditions. However, this was not possible for the current study in which multiple conditions were needed to examine the interactive effects of experimental manipulations. Nevertheless, excluding a large number of participants is typical in web-based studies, and ensures higher data quality as even a few extreme outliers can distort results (Cousineau & Chartier, 2010). The rate of exclusions is higher than lab-based research, but is lower than that in a related published online study using a version of the current task-switching paradigm (Reimers & Maylor, 2005).

Moreover, robust population mean estimates per condition can be obtained despite low trial numbers as the large sample sizes offset noise at the individual participant level (Reimers & Stewart, 2015). The number of trials per condition in the current study was adequate to demonstrate previously established effects and effect sizes (e.g. mixing and switching costs). Moreover, the adequacy of the number of trials to obtain reliable mean estimates was confirmed in an online study using a similar version of the current paradigm (Reimers & Maylor, 2005). Low trial numbers in online studies also have the benefit of reducing participant attrition, fatigue, and learning effects.

Connection to theories of cue switch cost

Two main theoretical explanations have arisen to account for the control processes that underlie cue and task switch costs. The two-component theory proposes separate components: an executive control task preparation process to intentionally configure a task using the cue, followed by an automatic task priming process to apply the task (Mayr & Kliegl, 2003). By contrast, the cue priming theory theories propose a single automatic priming process using the cue and stimulus (cue priming theories). Both theories propose cue switch costs and task switch costs, but the two-component theory proposes that these arise from separate components and involves executive control, while the cue priming theory proposes that a single priming process suffices.

The two-component theory builds on earlier models in task switching that had proposed separable processes for task preparation and priming.

Task preparation theories propose that switch costs are a result of executive control processes to configure the task in advance (Rogers & Monsell, 1995). Task and cue switch costs arise from active processes of using the cue to load rules for the current task into working memory from long-term memory, and then applying the retrieved rules to the stimulus (Mayr & Kliegl, 2000; Meiran, 2000; Meiran et al., 2000; Rogers & Monsell, 1995; Ruthruff et al., 2001; Sohn & Anderson, 2001). Task preparation theories have also been applied to mixing costs, as they propose an internal process to maintain readiness and to resolve interference in response to the stimulus across trials in a mixed block (Braver et al., 2003, 2009; Los, 1996, 1999; Lupker et al., 2003; Rubin & Meiran, 2005; Rubinstein et al., 2001). Meanwhile, task priming theories propose that task switch costs are due to leftover activation from the previous task that carries over and interferes with the current task (Allport et al., 1994; Allport & Wylie, 1999; Sohn & Anderson, 2001). Task priming theories have also been proposed to account for mixing costs, as interference from a previous task can persist over trials in a mixed block (Allport & Wylie, 1999; Waszak et al., 2003; Wylie & Allport, 2000). Although early theories focused on either task preparation or priming as explanations of the switch cost, later theories have proposed that task preparation and priming may both occur to produce a switch cost (reviews by Grange & Houghton, 2014; Kiesel et al., 2010; Meiran, 2010; Vandierendonck et al., 2010). Moreover, both processes are necessarily linked (Vandierendonck et al., 2010), as it is not possible to prepare for a task without also inhibiting a previous task (Monsell & Driver, 2000), and it is not possible to inhibit a task without simultaneously activating another (Dreisbach, 2012).

The cue priming theory proposes that the cue and stimulus are jointly encoded into a compound that uniquely determines the correct response (Logan & Bundesen, 2003, 2004; Schneider & Logan, 2005; Logan & Schneider, 2006; Schneider, 2016). The cue-stimulus compound is used to select a response. The current cue is compared to the previous cue in short-term memory and to other cues in long-term memory. Cue priming proposes a cue repetition benefit on trials with no cue change, as the cue is encoded more rapidly due to recency effects, thus response retrieval occurs more quickly. The single component of cue priming is proposed to account for both cue switch costs and task switch costs, without the need for additional components (Arrington & Logan, 2004, 2005; Arrington et al., 2007; Logan & Bundesen, 2003, 2004; Schneider, 2016). The cue-related process can occur over trials in a switch block (Logan & Bundesen, 2003, 2004; Schneider, 2016), and thus may also be linked to mixing cost.

The observed interaction between cue switch costs and mixing costs could be explained by either the two-component or cue priming theories. Both theories propose that cue encoding produces cue switch costs, and we would expect a longer cue encoding time in the mixed block (where the cue is informative) than in the pure block. In pure blocks, participants do not need to attend to the cue, thus they do not need to encode it and can maintain the relevant task-set in working memory. In mixed blocks, participants do need to encode the cue in order to select the relevant task-set (either using the joint cue and stimulus compound in the cue priming model, or via task-set reconfiguration in the preparation model). The current findings cannot differentiate between these theoretical accounts.

Conclusions

One of the most robust findings in the cognitive literature is that response latencies are longer when shifting a task than repeating a task. The switch cost has been commonly described as an index of cognitive control. Our findings align with past findings that switching enlists multiple control process in addition to executing a shift itself. Substantial costs were found when anticipating the possibility of a switch, and in using a cue to select a task, both of which were even larger than the actual cost of shifting a task. Moreover, the cue switch cost was dependent on the block context. Our results show that the switch cost is a complex phenomenon that arises from a number of processes, many of which are not switch-specific.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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