Stimulus- and Response-Based Interference Contributes to the Costs of Switching between Cognitive Tasks

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Abstract

Little is known about how stimulus- and response-based interference might interact to contribute to the costs of switching between cognitive tasks. We analyzed switch costs in a novel cued task-switching/card-matching paradigm in a large study ($N = 95$). We reasoned that interference from previously active task sets may be contingent upon the retrieval of these task sets via stimulus processing, or alternatively, via response processing. We examined the efficacy of these two factors through eligibility manipulations. That is, stimulus/response features that were capable of retrieving task sets from the previous trial remained eligible (or not) on the current trial. We report three main findings: First, no switch costs were found when neither stimulus features, nor response features, were adequate for the retrieval of the previously executed task sets. Second, we found substantial switch costs when, on switch trials, stimulus features kept the previously executed task eligible, and we found roughly equivalent switch costs when the previously executed response remained eligible. Third, evidence for stimulus-induced switch costs was exclusively observed when previously executed responses remained ineligible. These data indicate that stimulus-based interference, and of importance, response-based interference, contribute comparably to switch costs. Possible interpretations of non-additive switch costs are discussed.

Keywords: task switching; switch costs; stimulus-based interference; response-based interference

Supplementary materials.

Stimulus- and Response-Based Interference Contributes to the Costs of Switching between Cognitive Tasks

Cognitive multi-tasking takes place when subjects perform two tasks simultaneously, or when they switch from one task to another in rapid succession, also known as sequential multi-tasking. The costs of sequential multi-tasking are reflected in perseverative behavior as seen in clinical observations of brain-injured patients (Luria 1965). The Wisconsin Card Sorting Test (WCST; Berg 1948; Grant & Berg 1948) was used by Milner (1963) to assess perseveration, and since then, it has achieved a far-reaching dissemination in clinical neuropsychology (Demakis 2003; Nyhus & Barceló 2009; Strauss, Sherman, & Spreen 2006). This test requires sorting cards and using feedback to shift between different sorting rules. The WCST consists of cards depicting simple geometric figures that vary in color, shape, and number. Examinees have to sort cards in accordance with one of three viable rules, i.e., according to the color, shape, or number of the depicted object(s). In order to identify the currently valid sorting rule, they have to rely on verbal feedback, which is provided by the examiner on each trial. Positive feedback indicates that the valid sorting rule has been identified (e.g., sorting cards according to the color of the depicted object(s)), whereas negative feedback indicates that the applied sorting rule was invalid on that trial (e.g., negative feedback following a color sort implies that either card sorts according to the shape, or to the number, of the depicted object(s) was requested). Von Bastian and Druey (2017) considered the WCST as a task-switching paradigm at the judgment level in Kleinsorge and Heuer's (1999) hierarchically structured taxonomy of task-switching paradigms. Its indisputable complexity led to the conclusion that the WCST measures a number of basically inextricable psychological processes (Bishara et al. 2010)¹. As a result, experimental psychologists lost interest in card matching and used task switching to study perseverative tendencies (see Grange & Houghton 2014, for an overview). In the present work, we introduce a novel card-matching paradigm that enabled us to achieve two main goals: (a) To create a tool that may help bridge these two literatures (see also Kopp, Tabeing, Moschner, & Wessel 2006; Lange et al. 2015; 2016; 2018), and even more importantly, (b) to examine stimulus-based and response-based interference and their interaction in task switching. Below, we provide some essential background.

In task-switching paradigms, the primary index paralleling perseveration is switch costs. These are usually reflected in an increase in response times (RTs) or error rates for switch trials, where the task is different to that on the previous trial, relative to repeat trials, where the task is the same as on the previous trial. We focus on the cued task-switching design, where valid cues are presented prior to target stimuli to indicate the currently relevant task (Meiran 2014). One core finding is that switch costs are reduced (though not eliminated) with

increasing task preparation manipulated through cue-target intervals (CTIs; Grange & Houghton 2014; Kiesel et al. 2010; Monsell 2003; Vandierendonck, Liefvooghe, & Verbruggen 2010).

Switch costs are often taken to reflect the outcome of an update of cognitive task representations, also known as “sets”. Task sets refer to the preparatory state of the system, which enables it to select certain types of information and to ignore other information. Switch costs have been attributed (a) to target-related (reactive) task-set reconfiguration, i.e. to the incompleteness of cue-related (proactive) task representations (Meiran 2014), and (b) to interference-based carry-over effects from previous trials. In its simplest form, carry-over effects might emerge from task-set inertia, i.e., from slowly decaying task sets, which exert positive priming effects on task-repetition trials, but negative priming effects on task-switch trials (Allport, Styles, & Hsieh 1994).

More recent interference-based accounts of switch costs (see next paragraphs for detail) can be divided into two broad categories, stimulus-based interference (SBI) and response-based interference (RBI). An important means to study the effects of SBI on switch costs is by manipulating stimulus valence and congruency. Univalent target stimuli contain features of a single task (e.g., when executing parity/letter tasks, the target “#3” contains only parity-related information). Bivalent targets contain features for multiple tasks (e.g., “E3”, containing information relevant to both parity and letter tasks). Bivalent targets may be congruent (e.g., “E” and “3” are both mapped to the same response) or incongruent (e.g., “E” and “3” are mapped to the different responses). SBI effects on switch costs are robust, well-replicable phenomena (for overviews see Grange & Houghton 2014; Kiesel et al. 2010). Switch costs are usually massively reduced with univalent targets, whereas substantial switch costs emerge for bivalent stimuli (e.g., Jersild 1927; Koch & Allport 2006; Rogers & Monsell 1995; Spector & Biederman 1976;). Rogers and Monsell (1995) concluded that an irrelevant target attribute associated with the competitor task induces interference not only at the level of responses, but also at the level of tasks sets, because switch costs are smaller for univalent targets than for bivalent, congruent targets (Monsell, Taylor, & Murphy 2001; Rubin & Koch 2006). Taken together, there is evidence for SBI in task switching because targets activate relevant and irrelevant task sets as well as responses (Allport & Wylie 2000; Gilbert & Shallice 2002; Waszak, Hommel, & Allport 2003).

Another common finding in task switching is that response repetitions lead to improved performance on task-repetition trials (response-repetition benefit), but the response-repetition benefits are often abolished or reversed on task-switch trials (response-repetition cost; Kleinsorge & Heuer 1999; Mayr & Bryck, 2005; Rogers & Monsell 1995; Schuch & Koch 2004). These response-repetition effects have been replicated for different types of tasks and for all variants of task-switching paradigms (Kiesel et al. 2010, for review). Rogers and

Monsell (1995) proposed three possible explanations for response-repetition effects, i.e., the reconfiguration account, the association account, and the inhibition account. The reconfiguration account of response-repetition effects assumes that preparing a task switch also implies preparing a response switch (e.g., Kleinsorge & Heuer 1999). Association accounts of response-repetition effects assume that task execution strengthens associations between the executed response and the applied task set, while associations between the response and competitor task sets are weakened (Altmann 2011; Meiran 2000a,b; Schuch & Koch 2004). Response-repetition benefits occur on task-repetition trials due to the strengthened association between the re-executed response and the re-applied task set. In contrast, response-repetition costs occur on task-switch trials due to the weakened association between the re-executed response and the newly applied task set and/or the interference that originates from the strengthened association between the re-executed response and the previously applied task set. The inhibition account of response-repetition effects rests on the assumption that responses are inhibited after their execution to counteract perseverative tendencies (Smith 1968), resulting in a general inhibitory after-effect on response-repetition trials. Hübner and colleagues suggested that the inhibitory after-effect is compensated by task-repetition priming on response-repetition, task-repetition trials, but that the inhibitory after-effect adds to task-switch costs on response-repetition, task-switch trials (e.g., Druey 2014; Druey & Hübner 2008; Grzyb & Hübner 2013; Hübner & Druey 2006; Steinhauser, Hübner, & Druey 2009). Taken together, there is ample evidence for RBI in task switching, although there is a debate about which theoretical account may be able to explain the robust, well-replicable response-repetition effects best (see Gade, Schuch, Druey, & Koch 2014, for review; see also Koch, Frings, & Schuch 2018).

In this study, we combined SBI and RBI to pursue the following research goals: (a) According to previous evidence, SBI (as measured by target valence/congruency effects) and RBI (as measured by response-repetition effects) on switch costs should also be observed on our novel cued task-switching/card-matching paradigm. (b) Despite their robustness, the interaction of SBI and RBI has not yet been addressed in the literature. We designed our novel cued task-switching/card-matching paradigm such that it became possible to examine the interaction of SBI and RBI, as shortly outlined below.

Insert Figure 1 here

For the purpose that was described above, we introduced a novel eligibility manipulation. Figure 1 illustrates how the eligibility manipulation was realized. It exemplifies four show-case trials (labeled A-D), on each of which three response keys are available. The target response is indicated by the hand symbol on each trial. The previously executed response (R_{n-1}) had been mapped to one of the response keys (on all show-case

trials, R_{n-1} had always been mapped to the rightmost key). The response that was associated with the irrelevant feature of bivalent and incongruent targets (R_{bit}) was either mapped to the same key as R_{n-1} (Figure 1A & D), or alternatively, R_{n-1} and R_{bit} were mapped to two different keys (Figure 1B & C). Of importance, the eligibility manipulation implies that one response key was cued “away” (cf. the bracketed keys) on each trial such that the corresponding response remained ineligible on that trial (see Methods for procedural details).

Figure 1 also illustrates how the eligibility manipulation yields a factorial combination of SBI and RBI. Specifically, it allows to cue the R_{bit} -key away, rendering the response that is associated with the competitor task ineligible (Figure 1A & C) or eligible (Figure 1B & D). The manipulation of competitor-task eligibility parallels manipulating target valence/congruency: Competitor-task ineligibility corresponds to univalent targets, whereas competitor-task eligibility corresponds to bivalent/incongruent targets. The eligibility manipulation also allows to cue the R_{n-1} -key away, rendering the previous response ineligible (Figure 1A & B) or eligible (Figure 1C & D). The effects of SBI and RBI, as well as their interaction, on switch costs can be investigated by factorial combination on a trial-by-trial basis, as illustrated in Figure 1.

SBI and RBI effects on switch costs are robust, well replicable phenomena, but their interaction has not been addressed yet. The finding of an additive SBI by RBI interaction would provide evidence that interference-based switch costs emerge at independent levels of task processing. In contrast, the finding of a non-additive interaction would provide evidence that interference-based switch costs emerge at a common level of task processing.

Method

Participants

Ninety-five psychology students (81 undergraduates; 68 female; mean age = 23.2 yrs, $SD = 4.7$ yrs) participated for course credit or for a payment (10 €). No selection criteria other than that described above were used. All participants had normal or corrected-to-normal vision. Originally, the experiment was divided into three studies with $N = 25$ (initial study), $N = 40$ (follow-up study I) and $N = 40$ (follow-up study II) participants. However, the experimental manipulations that were specific to each of these studies (see Procedural Details) exerted only marginal effects on the measures of interest (cf. Supplementary Material, Tables A1, A2, A3). For sake of simplicity, we collapsed the data across the three studies, thereby including only the first data set from participants who participated in more than one study, leading to the final sample size of $N = 95$. This sample comprised $n = 25$ participants (24 undergraduates, 19 female, mean age = 22.8 yrs, $SD = 3.1$ yrs) from the initial study, $n = 36$ participants (33 undergraduates, 27 female, mean age = 23.7 yrs, $SD = 5.5$ yrs) from follow-up

study I, and $n = 34$ participants (23 undergraduates, 22 female, mean age = 23.0 yrs, $SD = 4.7$ yrs) from follow-up study II.

The initial study generated a first estimate of the effect sizes obtained in the Cued Card Matching Task (CCMT; see below for a description; the experimental materials, including an illustrative task video, are available in the Open Science Framework repository, [PERSISTENT WEB LINK WILL BE INCLUDED UPON ACCEPTANCE]). The highest order interaction on latency switch costs found in the initial study was associated with an effect size of $\eta_p^2 = .37$ (cf. Supplementary Material, Table A1). The follow-up studies were designed to have sufficient statistical power (i.e., $1-\beta = .95$) to find an effect of this size (with one numerator of freedom), given $\alpha = .01$. G-Power (Faul, Erdfelder, Lang, & Buchner 2007) indicated that a sample size of $N \geq 35$ was required.

The Cued Card Matching Task

The CCMT was programmed using OpenSesame (Mathôt, Schreij, & Theeuwes 2012). As shown in Figure 2 (as well as in the task video, which is available in the Open Science Framework repository, [PERSISTENT WEB LINK WILL BE INCLUDED UPON ACCEPTANCE]) on each trial, participants were required to match a response card (5.3×5.3 cm) to one of three horizontally aligned reference cards (3.7×3.7 cm each). Response cards and reference cards constituted the targets. The entire target-stimulus array measured 11.8 cm horizontally and 10.2 cm vertically. Response cards were presented at the center of the screen, whereas the reference cards appeared 6 cm above the center. The viewing distance amounted to 70 cm.

Response cards (yellow diamond, yellow triangle, red diamond, red star, green triangle, or green star) and reference cards (red triangle, green diamond, and yellow star) could be matched according to shape or color (i.e., two sorting rules, $r = 2$, and three rule features, $f = 3$, such that $c = 9$; see Footnote 1). We eliminated ambiguous response cards for which the correct reference card could have been based on two different features (e.g., the card that depicts a red triangle). Using task-switching jargon, all response cards were bivalent and incongruent, such that they afforded responses to two different reference cards on each trial. This feature of the CCMT implies that, on each trial, one of the three reference cards was not viable for responding (see Figure 2).

Insert Figure 2 here

As in the original WCST, responses were to be selected on the basis of the match between the relevant response-card feature and the corresponding reference-card feature. In the example that is depicted in Figure 2, matching according to SHAPE was requested. The response card shows a STAR, hence the reference card with a STAR shape was to be selected. Participants indicated the result of their matching by pressing (with the index,

middle, and ring finger of their right hand, respectively) one of three adjacent keys on the QWERTZ keyboard of a 17" notebook computer. The alignment of the three response keys (J , K , L) mapped to the spatial positions of the three reference cards on the screen (on the left, red triangle and key J , in the center green diamond and key K , on the right yellow star and key L).

Target stimuli remained on screen until a response was recorded. Time intervals between responses and onset of the next trial were held constant at 1000 ms. Erroneous responses were followed by a 400 Hz feedback tone presented for 100 ms. Notice that the CCMT is quite similar to the standard version of the WCST, with three exceptions: (1) The number of sorting rules (tasks) and the number of features per rule were reduced by one in order to reduce card-matching complexity. Task complexity amounts to $c = 9$ (compared to WCST- $c = 64$), given $r = 3-1 = 2$ and $f = 4-1 = 3$ (see Footnote 1). (2) An explicit task cue was introduced on each trial, which represents a well-established procedure in the task-switching literature (Meiran 2014). (3) Of importance, we introduced a novel cue type, which we refer to as a *response cue* that allowed keeping the competitor task and the previous response eligible on the current trial.

The relevant task was announced by written task cues (i.e., either the German word for shape [FORM] or for color [FARBE]). Task cues remained on screen for a duration of 300 ms. In addition, two response cues were presented 300 ms before task-cue onset such that these response cues were presented for a duration of 600 ms. Response-cue presentation commenced prior to task-cue onset to ensure that participants attend to the information provided by the response cues. Response cues consisted of two black squares matched in size to reference-card size. The spatial position of the two visible squares indicated those two reference cards that remained eligible on the current trial, whereas the omitted third square indicated the reference card that turned ineligible on that trial. To further facilitate processing of the response cues, the corresponding response keys (i.e., letters J , K , or L) were written in white capital letters (Calibri, bold, 60 pts) against the black background of the squares (e.g., the left response cue contained letter J).

The Factorial Design

Introducing response cues allowed us to examine how competitor-task eligibility (CTE) affected switch costs, as shown in Figure 3. The competitor task remained *eligible* when the two response cues rendered both viable reference cards eligible (cf. trial n of Figure 3). The competitor task turned *ineligible* when the two response cues rendered the irrelevant reference card ineligible (cf. Figure 2 and trials $n - 2$ and $n - 1$ of Figure 3). When competitor tasks remained eligible, response cards retained their bivalent and incongruent nature, that is, they afforded two different reference cards. Response cards emulated univalent targets when competitor tasks

were ineligible, that is, when they did not afford the irrelevant reference card. We refer to this experimental manipulation as CTE, with competitor task eligible (CTe) and competitor task ineligible (CTi) as the two factor levels.

Insert Figure 3 here

Response cuing provided novel opportunities to analyze the effects of trial-by-trial response variability on switch costs. If one assumes response alternation from trial to trial (the case of response repetition will be discussed below), there are two possibilities: First, as illustrated in Figure 3, the omitted response cue on trial n rendered the response that had been executed on trial $n - 1$ ineligible. Second, the omitted response cue on trial $n - 1$ left the response that had been executed on trial $n - 2$ eligible. Response cards thereby emulated univalent and bivalent responses, respectively. They emulated univalent responses when they afforded only those responses that were not executed on the preceding trial, which is equivalent to the ineligibility of the previously executed response. When the previously executed response remained eligible, they emulated bivalent responses. We refer to this experimental manipulation as previous response eligibility (PRE), with previous response ineligible (PRi) and previous response eligible (PRe) as factor levels.

The introduction of response cues made it possible to manipulate CTE and PRE on a trial-by-trial basis in a factorial design. Four eligibility conditions e emerged, with $e \in \{\text{CTi-PRi}, \text{CTe-PRi}, \text{CTi-PRe}, \text{CTe-PRe}\}$ (see Figure 1). These four conditions could be crossed with the two levels of the task sequence factor (repeat vs. switch trials), yielding eight conditions $e \in \{(\text{CTi-PRi}, \text{CTe-PRi}, \text{CTi-PRe}, \text{CTe-PRe}) \mid \text{task repeat}, (\text{CTi-PRi}, \text{CTe-PRi}, \text{CTi-PRe}, \text{CTe-PRe}) \mid \text{task switch}\}$. It was however not possible to cross every level of these three factors with the response sequence factor (repetition vs. alternation) because response repetitions were impossible when previous responses were ineligible. This forced us into a nested layout with twelve conditions, $e \in \{(\text{CTi-PRi}, \text{CTe-PRi}, \text{CTi-PRe}, \text{CTe-PRe}) \mid \text{task repeat} \mid \text{response alternation}, (\text{CTi-PRi}, \text{CTe-PRi}, \text{CTi-PRe}, \text{CTe-PRe}) \mid \text{task switch} \mid \text{response alternation}, (\text{CTi-PRe}, \text{CTe-PRe}) \mid \text{task repeat} \mid \text{response repetition}, (\text{CTi-PRe}, \text{CTe-PRe}) \mid \text{task switch} \mid \text{response repetition}\}$.

Procedural Details

The sample ($N = 95$) was composed of three subsamples (see Participants) because we were manipulating two additional variables that finally proved to exert only marginal effects on the measures of interest. One of the two variables constituted CTI that was defined as the time that elapsed between the onset of response cues and target onset (see Figure 2). For a subsample of $n = 61$ participants (from the initial study plus the follow-up study I), CTIs were manipulated at two levels, with CTI = 700 ms (short CTI) and CTI = 1500 ms

(long CTI), whereas CTI was held constant for the remaining participants ($n = 34$ follow-up study II), with CTI = 1100 ms. After having established that the CTI manipulation did not exert recognizable effects on switch costs (cf. Supplementary Material, Tables A1, A2, A3), all data were collapsed in the analyses of variance (ANOVAs) that we report.

Another variable relates to trial-by-trial response variability (cf. Table 1). The subsample of $n = 25$ participants (initial study) was biased toward response repetition ($P = .67$) on those trials where previous responses remained eligible ($P = .75$). Overall, response repetitions and response alternations were in equilibrium in that subsample ($P = .25$ (ineligible trials) + $P = .33 \times .75$ (eligible trials) with $P = .50$ alternations vs. $P = .67 \times .75$ (eligible trials) with $P = .50$ repetitions). The subsample of $n = 36$ participants (follow-up study I) was biased toward response alternation ($P = .67$) on those trials where previous responses remained eligible. Overall, response repetitions and response alternations were not in equilibrium in that subsample ($P = .25$ (ineligible trials) + $P = .67 \times .75$ (eligible trials) with $P = .75$ alternations vs. $P = .33 \times .75$ (eligible trials) with $P = .25$ repetitions). The third subsample of $n = 34$ participants (follow-up study II) was neither biased toward response repetition nor toward response alternation ($P = .50$) on those trials where previous responses remained eligible. Overall, response repetitions and response alternations were not in equilibrium in that subsample ($P = .50$ (ineligible trials) + $P = .50 \times .50$ (eligible trials) with $P = .75$ alternations vs. $P = .50 \times .50$ (eligible trials) with $P = .25$ repetitions). After having established that these context manipulations did not exert recognizable effects on switch costs (cf. Supplementary Material, Tables A1, A2, A3), data from all subsamples were collapsed in the ANOVAs that we report.

Insert Table 1 here

Table 1 shows that 60 or 120 trials were administered in each of the twelve conditions, resulting in a total number of 960 trials. These trials were presented in three trial blocks of 320 trials each. Pseudorandomized sequences of trials were created to ascertain that each of the conditions consisted in the desired trial numbers. Table 1 presents the number of trials across conditions before and after exclusion of stimulus-repetition trials.

Participants were instructed to pay attention both to the response cues and to the task cue. Prior to the experimental sequence, participants' understanding of the task was ascertained by running 32 practice trials. The experiment was run in a quiet and comfortably illuminated room, and lasted about 90 minutes.

Data Analysis

Mean RTs on correct trials served as the primary dependent variable for each individual. Trials with RTs faster than 100 ms and slower than three *SD* above the individual mean RTs of all trials ($< 0.01\%$ and

1.7%, respectively) were excluded from analyses. The trimming criterion was selected a priori to data analyses. Stimulus-repetition trials were excluded from analyses (15.6% of the remaining valid trials). In addition to the error trials (cf. Supplementary Material, Table A4), rarely occurring “odd”-error trials (i.e., when the non-viable reference card was chosen, < 0.01%) and post-error trials (2.6%) were excluded from analyses. Percent errors (PE) are also considered to check for potential speed-accuracy trade-offs.

In addition, the linear integrated speed-accuracy score (LISAS; Vandierendonck 2017) was computed. LISAS (see equation (1)) represents an integrated measure (in arbitrary units, a.u.) that is based on a linear combination of RTs and PE,

$$\text{LISAS} = RT_j + \frac{S_{RT}}{S_{PE}} \times PE_j \quad \text{equation (1)}$$

where RT_j is a participant's mean RT in condition j , PE_j is a participant's mean PE in condition j , S_{RT} a participant's overall RT standard deviation, and S_{PE} a participant's overall PE standard deviation. LISAS yields an estimate of latency corrected for the proportion of errors. The weighting of the contribution of PE with the ratio of RT and PE standard deviations is done to achieve a similar weight of the two components.

Vandierendonck (2017) recommended refraining from calculating the LISAS when RT and PE are negatively correlated, but this was not the case in any of our conditions (cf. Supplementary Material, Table A5).

Statistical significance was determined at $\alpha = .01$. Greenhouse-Geisser corrected p -values are reported for all main effects and interactions that involve factors with more than two levels, but original degrees of freedom are reported.

Results

Description of Results

Figure 4 displays the data for the three dependent variables (RTs, PE, LISAS) across conditions, that is Task Transition (repeat, switch), CTE (ineligible, eligible), and the nested factor Response Variability (PRi | response alternation, PRe | response alternation, PRe | response repetition) (cf. for the numerical data Supplementary Material, Table A4).

Insert Figure 4 here

Inspection of Figure 4 reveals several potentially interesting findings. First, when previous responses remained ineligible (i.e., on PRi trials), the CTE manipulation seemed to modulate RTs, PE, and LISAS in similar ways. Notably, the eligibility of competitor tasks (i.e., on CTe trials) produced large switch costs, whereas no switch costs seemed to emerge when competitor tasks remained ineligible (i.e., on CTi trials). Second, when previous responses were eligible (i.e., on PRe trials), response sequence seemed to moderate RTs,

PE, and LISAS in different ways. Large latency-switch costs could be observed on response-repetition trials, whereas virtually no latency switch costs emerged on response-alternation trials, where switch costs seemed to be confined to enhanced inaccuracy of responding. Third, the CTE manipulation did not exert additional effects on integrated switch costs (i.e., LISAS) when previous responses were eligible (i.e., on PRe trials) because integrated switch costs were very similar on CTi- and CTe-trials—a finding that contrasts with the data from PRi trials.

Omnibus ANOVAs

We commenced statistical inference with three three-way repeated-measures omnibus ANOVAs (Table 2). Task Transition (repeat, switch), CTE (ineligible, eligible), and Response Variability (PRi | response alternation, PRe | response alternation, PRe | response repetition) served as repeated-measures variables. RTs, PE, and LISAS served as dependent variables. The mean number of correct trials per cell after exclusion of all to-be-excluded trials (see Methods for criteria) was 36.8–79.4 (minimum number of trials per cell 20–54).

Insert Table 2 here

For all dependent variables, the main effect of Task Transition proved statistically significant, with overall faster and more accurate responses on repeat trials (Figure 4). Of more importance were the statistically significant interactions involving Task Transition that were obtained, with the highest-order interaction being Task Transition $\times$ CTE $\times$ Response Variability. We did not parse this three-way interaction into its constituents because the nested factor, Response Variability, complicated these analyses. For that reason, Response Variability was fragmented in two partly overlapping factors: one which considers response-alternation trials only, and one which considers PRe trials only.

Response-Alternation Trials

Three separate three-way repeated-measures ANOVAs with Task Transition (repeat, switch), CTE (ineligible, eligible), and PRE (ineligible, eligible) as repeated-measures variables were conducted on RTs, PE, and LISAS for response-alternation trials only (Table 3). In these analyses, responses are not repeated across consecutive trials, but previous responses—as well as competitor tasks—may be ineligible or eligible. These analyses allow examining the effects of CTE, PRE, and their interaction on switch costs, without further complicating the analyses. We again found statistically significant interactions involving Task Transition on each of the three dependent variables, with the highest-order interaction being Task Transition $\times$ CTE $\times$ PRE. This interaction indicates that switch costs were modulated by CTE and PRE in a non-additive manner, suggesting that stimulus-related and response-related switch costs emerge at a common level of task processing..

Insert Table 3 here

To further parse this three-way interaction, we conducted separate ANOVAs for PRi and PRe trials. For latency switch costs, we found a statistically significant interaction Task Transition $\times$ CTE, $F(1, 94) = 57.29, p < .001, \eta_p^2 = .38$, when the previous response was ineligible (i.e., on PRi trials), indicating modulatory effects of target eligibility on latency switch costs (CTi: $M = -14$ ms, $SE = 7$; CTe: $M = 65$ ms, $SE = 6$; see Figure 4). In contrast, when the previous response was eligible (i.e., on PRe trials), we found neither a statistically significant main effect of Task Transition, $F(1, 94) = 2.13, p = .148, \eta_p^2 = .02$, nor evidence for a statistically significant two-way interaction Task Transition $\times$ CTE, $F(1, 94) = 2.37, p = .127, \eta_p^2 = .03$ (CTi: $M = 16$ ms, $SE = 5$; CTe: $M = 1$ ms, $SE = 9$; see Figure 4). Neither latency switch costs nor effects of CTE on latency switch costs were discernible on PRe trials.

Very similar results emerged in the PE analysis with separate ANOVAs for PRi and PRe trials for accuracy switch costs. There was a statistically significant two-way interaction on PRi trials, indicating a modulatory effect of CTE on accuracy switch costs, Task Transition $\times$ CTE, $F(1, 94) = 48.78, p < .001, \eta_p^2 = .34$ (CTi: $M = 0.80$ %, $SE = 0.23$; CTe: $M = 3.43$ %, $SE = 0.41$; see Figure 4). Analysis of PRe trials indicated a statistically significant main effect of Task Transition, $F(1, 94) = 57.58, p < .001, \eta_p^2 = .38$, but no statistically significant interaction Task Transition $\times$ CTE, $F(1, 94) = 0.21, p = .647, \eta_p^2 < .01$ (CTi: $M = 1.73$ %, $SE = 0.27$; CTe: $M = 1.92$ %, $SE = 0.36$; see Figure 4). Accuracy switch costs were detectable, but effects of CTE on accuracy switch costs were not verifiable on PRe trials.

The LISAS analysis further corroborated the findings that were obtained from RTs and PE. We found a statistically significant interaction on PRi trials, Task Transition $\times$ CTE, $F(1, 94) = 90.78, p < .001, \eta_p^2 = .49$, indicating modulatory effects of CTE on integrated switch costs (CTi: $M = 0$ a.u., $SE = 9$; CTe: $M = 132$ a.u., $SE = 12$; see Figure 4). On PRe trials, there was a statistically significant main effect of Task Transition, $F(1, 94) = 27.98, p < .001, \eta_p^2 = .23$, but no statistically significant interaction Task Transition $\times$ CTE, $F(1, 94) = 1.10, p = .298, \eta_p^2 = .01$ (CTi: $M = 54$ a.u., $SE = 8$; CTe: $M = 38$ a.u., $SE = 14$; see Figure 4). Integrated switch costs were detectable, but CTE did not exert discernible effects on integrated switch costs on PRe trials.

Taken together, the analyses of response-alternation trials show that CTE modulated switch costs as long as the previous responses remained ineligible. Ineligible competitor tasks were associated with negligible switch costs, while eligible competitor tasks induced appreciable switch costs. Furthermore, CTE and PRE showed non-additive interaction because CTE lost its otherwise strong influence on switch costs when previous

responses were eligible. Overall, this pattern of findings seems to be commensurable with the assumption of a non-additive interaction between stimulus-related and response-related contributions to switch costs.

Pre Trials

Three three-way repeated-measures ANOVAs with Task Transition (repeat, switch), CTE (ineligible, eligible), and Response Sequence (alternation, repetition) as repeated-measures variables were performed for those trials where the previous response remained eligible across consecutive trials (Table 4). These analyses allow examining the effects of CTE, Response Sequence, and their interaction on switch costs without further complicating the analyses.

Insert Table 4 here

We found statistically significant interactions involving Task Transition (Figure 4). Latency switch costs revealed an interaction between Task Transition and Response Sequence, with overall more pronounced latency switch costs for repeated responses than for alternating responses. The three-way interaction Task Transition $\times$ CTE $\times$ Response Sequence was non-significant. Accuracy switch costs revealed a statistically significant three-way interaction Task Transition $\times$ CTE $\times$ Response Sequence. After integration of RTs and PE into LISAS, the two-way interaction (Task Transition $\times$ Response Sequence) proved statistically significant. Furthermore, the statistically significant two-way interactions Task Transition $\times$ CTE for RTs and PE seemed to cancel each other (speed-accuracy trade off) since the LISAS analysis did not reveal statistical significance of this two-way interaction ($F < 1$). In sum, latency switch costs were strongly modulated by Response Sequence, with larger latency switch costs for repeated responses than for alternating responses. CTE did in no way exert detectable influences on integrated switch costs. Overall, these findings corroborate the absence of stimulus-related contributions to switch costs when previous responses remain eligible.

Discussion

Previous studies have convincingly shown stimulus-related and response-related contributions to switch cost, but information on the interaction between SBI and RBI so far lacking. The present study was designed to address this shortcoming. Following previous authors (Allport & Wylie 2000; Gilbert & Shallice 2002; Waszak et al. 2003), we found evidence for a contribution of SBI to switch costs. Importantly, we also found evidence that RBI also contributed to switch costs. These response-related contributions to switch costs were modulated by response repetition, with larger costs for repeated responses than for alternating responses. A major conclusion from our data is that stimulus-based interference and response-based interference both contribute to switch costs, in roughly equivalent strength. An additional novel finding was that stimulus-task binding

contributed to switch costs solely when previously executed responses remained ineligible, whereas no stimulus-related switch costs were discernible when previous responses were eligible (i.e., non-additive switch costs).

These results are novel because our estimates of RBI are not biased through confounding variables. Whereas the stimulus contribution to the retrieval of the previous task set has been unambiguously demonstrated (e.g., Waszak et al. 2003), this is less true for the response contribution. One reason for this state of affairs may be that the investigation of response-set binding is challenging due to a number of inherent problems with potential confounders. Most notably, there is no simple way to manipulate response valence. This is because the utilization of univalent response mappings confounds task switches and response-set switches on switch trials (Kieffaber, Kruschke, Cho, Walker, & Hetrick 2013; Mayr 2001; Meiran 2000a; Mueller, Swainson, & Jackson 2007; West, Bailey, & Langley 2009). Univalent target stimuli (e.g., when executing parity/letter tasks, the target “#3” contains only parity-related information) are mapped to distinct response sets to different tasks in univalent response mappings (e.g., parity task, “odd” = left index finger, “even” = left middle finger, letter task, “vowel” = right index finger, “consonant” = right middle finger). In contrast, bivalent targets (e.g., “E3”, containing information relevant to both parity and letter tasks) are mapped to a response for both tasks in bivalent response mappings (e.g., “odd” *and* “vowel” = right index finger, “even” *and* “consonant” = right middle finger). As a result, task switches are inextricably liaised with response-set switches in univalent response mappings. This confound is however not present in bivalent response mappings, thereby introducing a bias toward smaller estimates of response-valence contributions to switch costs.

Our data are compatible with associative learning accounts of switch costs, according to which switch costs derive from associations between perceptual, motor, and cognitive representations (Abrahamse, Braem, Notebaert, & Verguts 2016; Altmann 2011; Hazeltine & Schumacher 2016; Schmidt & Liefvooghe, 2016; Verbruggen, Stevens, & Chambers 2014). In this framework, stimulus-related contributions to switch costs arise from stimulus-task associations (Allport & Wylie 2000; Gilbert & Shallice 2002; Waszak et al. 2003), whereas response-related switch costs arise from response-task associations.

Specifically, the reported non-additive three-way interaction can be partially accounted for by the event-coding framework (see also Mayr & Bryck, 2005, for related concepts). The event-coding framework (Hommel, Müsseler, Aschersleben, & Prinz 2001; Hommel 2004) assumes exhaustive associations (i.e., event files). It assumes that a transient, episodic “event file” is created on each trial (Hommel et al. 2001). According to Hommel and colleagues, an event file is a network of bindings that temporarily links codes of perceptual

features, accompanying actions, and task context. Encounters with one or more bound elements cause the retrieval of the entire event file through an automatic pattern completion process (Hommel 2004). The event coding model provides an explanation for valence effects contributing to switch costs, because both bivalent targets and bivalent response mappings trigger the retrieval of event files that were created on previous trials, thereby inducing switch costs on switch trials. Note that this model makes similar predictions regarding stimulus-based and response-based task-set retrieval, as the target, the response, and the task set are all bound together in one single event file. It therefore provides a parsimonious account of non-additive switch costs. This holds true because eligible competitor tasks and eligible previous responses serve as retrieval cues for self-completing event files. Due to their hypothesized pattern completion characteristic, these event files operate like logical “or”-gates, with the following “input $\rightarrow$ output”-relations: $00 \rightarrow 0$, $10 \rightarrow 1$, $01 \rightarrow 1$, $11 \rightarrow 1$. This implies that there are no switch costs (output) when both retrieval cues (input) are ineligible, but there are switch costs of similar strength when one or more retrieval cues are eligible, leading to the prediction of non-additive switch costs. However, the comparatively low switch costs on conditions that involve eligible previous responses when responses alternate from trial to trial cannot be easily reconciled with the event-coding framework.

Non-associative accounts of switch costs are able to explain why stimulus-set costs are conditioned on previous responses remaining ineligible. As one possibility, dual interference might represent a circumstance requiring cognitive control (e.g., Koch, Gade, Schuch, & Philipp 2010; Mayr, Kuhns, & Rieter 2013; Miller & Cohen 2001; Rubinstein, Meyer, & Evans 2001). Specifically, feature-based selective attention (Bichot, Heard, DeGennaro, & Desimone 2015; Desimone & Duncan 1995) might be triggered by response-task interference. That is, attentional selectivity might be raised when response cues indicate that previously executed responses will remain eligible on the current trial. The evocation of feature-based selective attention might bias the system toward processing solely the task-relevant feature of response cards (e.g., their shape, but not their color, when SHAPE is the task), thereby relieving it from stimulus-task interference, even when competitor tasks remain eligible.

In line with previous findings (e.g., Schuch & Koch 2003), our data also imply that the presence of response-related switch costs depends heavily on the repeated execution of responses that have been associated with previously active task sets on preceding trials. Meiran and colleagues (Meiran 2000a; Meiran, Kessler, & Adi-Japha 2008) developed computational models of switch costs. The models of Meiran (2000a; M-2000 model) and Meiran and colleagues (2008; “control by action representation and input selection”, CARIS model)

share similarities, but there are also critical differences. The core assumption of the M-2000 model was that task switching implies changes in how stimuli and/or responses are interpreted, and that these changes have distinct temporal loci, and thus that they are independent. However, one conclusion that was drawn from Meiran and colleagues' (2008) work was that stimulus-sets and response-sets cannot be controlled independently during task switching. In this respect, the current findings are more in line with Meiran and colleagues' (2008) conclusion.

One of the limitations of our study is that we cannot draw conclusions about the interaction between associative task bindings and task preparation based on these data. Apparently, our CTI manipulations (i.e., 700 ms and 1500 ms, respectively) were not sufficiently divergent to uncover potential interactions. Likewise, it remains to be seen how the relative timing of the onset of response cues and tasks cues affected the findings. In our study, response cues appeared always before task cues, with a relative earlier onset of response cues in comparison to task cues (300 ms). Effects of these temporal variables need to be addressed in future studies³.

An important distinction between Waszak et al.'s (2003) conception of stimulus-task binding and the conception here is that the former was assumed to be very long lasting, and the latter very transient (trial-by-trial carry-over). Thus, we were specifically interested in the carry-over of any binding that might occur with task sets and that might be formed on the previous trial rather than on long-term learning. One hypothesis for the interaction between immediate response repetition effects and switch costs, first reported by Rogers and Monsell (1995), was that the response on the previous trial has become associated with the task performed so that the task required on the current trial biases response selection (e.g., Altmann 2011, Druey 2014). We discuss the interaction between response repetition and switch costs in the Supplementary Materials in more detail.

Taken together, our data lend some credibility to associative models of switch costs (Abrahamse et al. 2016; Altmann 2011; Hazeltine & Schumacher 2016; Verbruggen et al. 2014). The binding framework accounts for the findings via transient, elemental associations between stimuli and task sets and between responses and task sets, respectively, plus a to-be-specified mechanism for handling dual interference. The event-coding model (i.e., the formation of associative links between stimuli, responses, and tasks sets; cf. Hommel et al. 2001; Hommel 2004) offers a more parsimonious account of non-additive switch costs. However, cognitive-control models are likewise suitable to account for the non-additive variations in switch costs that we observed.

Compliance with Ethical Standards

The authors declare that they have no conflict of interest. All procedures performed in studies involving human participants were in accordance with the local Ethics Committee at the Department of Psychology (Technische Universität Braunschweig, B-2016-14) and with the 1964 Helsinki declaration and its later

amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

Data Availability Statement

The datasets generated during and/or analyzed during the current study are available in the Open Science Framework repository, [PERSISTENT WEB LINK WILL BE INCLUDED UPON ACCEPTANCE].

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Footnotes

¹The WCST is often criticized for its complexity, which originates from arbitrary features of the standard material. Let r be the number of sorting rules, and let f be the number of rule features ($r = 3, f = 4$ for the WCST). There are f distinct response cards (Dehaene & Changeux 1991), rendering the WCST a complex task requiring sufficient intellectual comprehension. f may be considered as a general metric of card-matching complexity, c , with $\text{WCST-}c = 64$.

²The terms “stimulus-task” and “response-task” mean something completely different and should not be confused with similar terms used by Meiran (2000a,b): Here they mean that the stimulus (or response) gets bound with the task set. In Meiran’s theory, the terms “stimulus-set” and “response-set” meant to represent two separate aspects of what we call here “task set”. The idea in that theory was that task sets are conglomerates of representations that include which aspects of the stimulus are attended/ignored (stimulus-set) and which parts of the response (representation) are attended/ignored—the “response-set”.

³Note that we conducted a control study in which the eligibility of reference cards/responses was manipulated by deleting one of the three reference cards instead of introducing response cues. The observed two-way interaction effect of Task Transition and CTE that we obtained in the control study parallels the findings that were reported on PRi trials in the main study. This result suggests that the presence of a two-way interaction effect in the main study cannot be attributed to the introduction of response cues. Please see the supplementary material for details.

Table 1

Absolute number of trials in the three subsamples (i.e., Initial Study, Follow-Up Study 1, and Follow-Up Study 2, separately for response-alternation and response-repetition trials, as well as for previous response ineligible (PRi) and previous response eligible (PRe) trials and for task repeat and task switch trials, respectively.

		Response Alternation				Response Repetition	
		PRi		PRe		PRe	
	Task Transition	CTi	CTe	CTi	CTe	CTi	CTe
Initial Study	Repeat	60 (60)	60 (60)	60 (60)	60 (60)	120 (60)	120 (63)
	Switch	60 (33)	60 (60)	60 (60)	60 (39)	120 (120)	120 (120)
Follow-Up 1	Repeat	60 (60)	60 (60)	120 (120)	120 (120)	60 (36)	60 (39)
	Switch	60 (39)	60 (60)	120 (120)	120 (57)	60 (60)	60 (60)
Follow-Up 2	Repeat	120 (120)	120 (120)	60 (60)	60 (60)	60 (24)	60 (36)
	Switch	120 (57)	120 (120)	60 (60)	60 (24)	60 (60)	60 (60)

Note. Number of trials per cell after exclusion of stimulus repetitions in parentheses. CTe = competitor task eligible; CTi = competitor task ineligible.

Table 2

Overall ANOVA results for Task Transition (repeat, switch), CTE (ineligible, eligible), and Response Variability (PRi | response alternation, PRe | response alternation, PRe | response repetition) for RTs, PE, and LISAS. N = 95

	<i>df1</i>	<i>df2</i>	RTs			PE			LISAS		
			<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2
Task Transition	1	94	77.73	< .001	.45	85.16	< .001	.48	111.11	< .001	.54
CTE	1	94	2.90	.092	.03	47.95	< .001	.34	28.80	< .001	.24
Response Variability	2	93	14.62	< .001	.24	10.09	< .001	.18	19.14	< .001	.29
Task Transition × CTE	1	94	2.10	.150	.02	42.80	< .001	.31	22.58	< .001	.19
Task Transition × Response Variability	2	93	23.94	< .001	.34	0.45	.688	.01	13.34	< .001	.22
CTE × Response Variability	2	93	24.37	< .001	.34	10.54	< .001	.19	26.70	< .001	.37
Task Transition × CTE × Response Variability	2	93	29.35	< .001	.39	10.96	< .001	.19	28.70	< .001	.38

Note. CTE = competitor-task eligibility; LISAS = linear integrated speed-accuracy score; PE = percent errors; PRe = previous response eligible; PRi = previous response ineligible; RTs = response times.

Table 3

ANOVA results for Task Transition (repeat, switch), CTE (ineligible, eligible), and PRE (ineligible, eligible) for RTs, PE, and LISAS on response-alternation trials. N = 95

	<i>df1</i>	<i>df2</i>	RTs			PE			LISAS		
			<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2
Task Transition	1	94	16.40	< .001	.15	91.28	< .001	.49	72.18	< .001	.43
CTE	1	94	0.07	.799	< .01	56.01	< .001	.37	17.14	< .001	.15
PRE	1	94	7.95	.006	.08	0.04	.844	< .01	5.54	.021	.06
Task Transition × CTE	1	94	22.49	< .001	.19	24.17	< .001	.21	30.75	< .001	.25
Task Transition × PRE	1	94	6.94	.010	.07	0.90	.345	.01	4.49	.037	.05
CTE × PRE	1	94	34.20	< .001	.27	21.31	< .001	.19	48.91	< .001	.34
Task Transition × CTE × PRE	1	94	39.89	< .001	.30	19.92	< .001	.18	52.22	< .001	.36

Note. CTE = competitor-task eligibility; LISAS = linear integrated speed-accuracy score; PE = percent errors; PRE = previous response eligibility; RTs = response times.

Table 4

ANOVA results for Task Transition (repeat, switch), CTE (ineligible, eligible), and Response Sequence (alternation, repetition) for RTs, PE, and LISAS on previous response eligible trials. N = 95

	<i>df1</i>	<i>df2</i>	RTs			PE			LISAS		
			<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2	<i>F</i>	<i>p</i>	η_p^2
Task Transition	1	94	56.27	< .001	.37	61.87	< .001	.40	83.23	< .001	.47
CTE	1	94	0.34	.561	< .01	19.19	< .001	.17	4.35	.040	.04
Response Sequence	1	94	29.49	< .001	.24	14.18	< .001	.13	36.05	< .001	.28
Task Transition $\times$ CTE	1	94	11.17	.001	.11	13.68	< .001	.13	0.20	.659	< .01
Task Transition $\times$ Response Sequence	1	94	47.69	< .001	.34	0.17	.684	< .01	26.96	< .001	.22
CTE $\times$ Response Sequence	1	94	40.47	< .001	.30	4.88	.030	.05	29.72	< .001	.24
Task Transition $\times$ CTE $\times$ Response Sequence	1	94	1.69	.197	.02	10.69	.002	.10	0.76	.386	.01

Note. CTE = competitor-task eligibility; LISAS = linear integrated speed-accuracy score; PE = percent errors; RTs = response times.

Figure 1

Fig. 1 An illustration of the cuing-away technique with three viable responses on each trial; the bracketed responses are cued away (see Method for details). The hand symbols represent target responses. The label R_{n-1} represents the previously executed response. The label R_{bit} represents the response that is associated with the currently irrelevant (“competitor”) task that is conveyed by bivalent targets. **A.** The R_{n-1} -key and the R_{bit} -key are both ineligible. **B.** The R_{n-1} -key is ineligible while the R_{bit} -key remains eligible. **C.** The R_{bit} -key is ineligible while the R_{n-1} -key remains eligible. **D.** The R_{n-1} -key and the R_{bit} -key are both eligible.

Figure 2

Fig. 2 An exemplified trial on the Cued Card Matching Task (CCMT). Response cues, task cues and targets followed each other in that order. Three reference cards and one response card constituted the target, and both types of cards depicted colored geometrical shapes. The task required matching the response card against the three horizontally aligned reference cards. On each trial, two tasks were possible: color or shape. In our example trial, the red star matches the red triangle (identical with regard to color), and it matches the yellow star (identical with regard to shape), but there is no match between the red star and the green diamond (hence the middle reference card is not viable for responding). The correct response to the relevant task SHAPE is STAR, to be indicated by choosing the right reference card. The response to the irrelevant (competitor) task COLOR would be RED, to-be-indicated by choosing the left reference card. The two response cues *K* and *L* render both the middle (non-viable) and the right (shape task) reference card/response eligible. The omitted response cue *J* renders the left (color task) reference card/response ineligible. Hence, the depicted trial exemplifies the *ineligible competitor-task condition*. An illustrative task video is available [in the Open Science Framework repository](#), [PERSISTENT WEB LINK WILL BE INCLUDED UPON ACCEPTANCE].

Figure 3

Fig. 3 Three exemplified consecutive trials on the Cued Card Matching Task (CCMT). Two tasks are possible on each trial, that is, color and shape. Trial n shows an “eligible competitor task” (CTe), “ineligible previous response” (PRi) trial. Here, the correct response is DIAMOND, hence the middle reference card (K key). Given the two response cues on trial n , the irrelevant task (color) remains eligible (RED, left response card). In contrast, the previous response (i.e., the L key on trial $n - 1$) is made ineligible by the response cues. Trial $n - 1$ shows an “ineligible competitor task” (CTi), “eligible previous response” (PRe) trial. Here, the correct response is STAR, hence the right reference card (L key). Given the two response cues on trial $n - 1$, the irrelevant task (color) is made ineligible (GREEN, middle response card) by the response cues. In contrast, the previous response remains eligible (i.e., the J key on trial $n - 2$). CTi = competitor task ineligible; CTe = competitor task eligible; PRe = previous response eligible; PRi = previous response ineligible.

Figure 4

Fig 4. Mean RTs, PE and LISAS (a.u., arbitrary units) separately for task-switch and task-repeat trials, and across CTE (ineligible, eligible) and Response Variability (PRi | response alternation, PRe | response alternation, PRe | response repetition). Error bars represent the 99 percent repeated-measures confidence interval (Hollands & Jarmasz 2010) for the omnibus three-way interaction effect of Task Transition, CTE, and Response Variability. $N = 95$. CTE = competitor-task eligibility; CTe = competitor task eligible; CTi = competitor task ineligible; LISAS = linear integrated speed-accuracy score; PE = percent errors; PRe = previous response eligible; PRi = previous response ineligible; RTs = response times.