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THEORETICAL REVIEW

Monitoring and control in multitasking

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Abstract
The idea that conflict detection triggers control adjustments has been considered a basic principle of cognitive control. So far, this "conflict-control loop" has mainly been investigated in the context of response conflicts in single tasks. In this theoretical position paper, we explore whether, and how, this principle might be involved in multitasking performance, as well. We argue that several kinds of conflict-control loops can be identified in multitasking at multiple levels (e.g., the response level and the task level), and we provide a selective review of empirical observations. We present examples of conflict monitoring and control adjustments in dual-task and task-switching paradigms, followed by a section on error monitoring and posterror adjustments in multitasking. We conclude by outlining future research questions regarding monitoring and control in multitasking, including the potential roles of affect and associative learning for conflict-control loops in multitasking.

Keywords Cognitive control · Conflict monitoring · Error monitoring · Dual tasks · Task switching · Affect · Crosstalk

Broadly considered, the term *cognitive control* refers to those processes that help gear our behavior toward the currently pursued goals. One example of cognitive control is that the detection of (cognitive) conflict triggers adjustments of subsequent cognitive processing (Botvinick, Braver, Barch, Carter, & Cohen, 2001). This idea has become very popular in cognitive psychology over the past 15 years and has stimulated numerous empirical investigations. Mostly, however, investigations have been restricted to conflict arising in single-task contexts (for reviews, see, e.g., Dreisbach & Fischer, 2012b; Duthoo, Abrahamse, Braem, Boehler, & Notebaert, 2014a, b; Egner, 2007, 2017). Yet, in everyday life we are rarely engaged in only one task, but typically perform multiple tasks at the same time. In other words, we are almost always engaged in *multitasking*. In the present article, we explore whether and how the principles of conflict monitoring and control adjustment apply to multitasking situations. We will argue that several kinds of conflict-control loops can be identified in multitasking performance, including conflict-control loops at the task level.

The aim of the present review is to explore the role of conflict monitoring and control adjustments in dual-task and task-switching paradigms, on both theoretical and empirical levels. We propose that the theoretical perspective of conflict-control loops in multitasking provides a useful framework for integrating several empirical phenomena in the dual-task and task-switching literature.

We will start with a brief overview of multitasking paradigms in cognitive psychology, followed by a brief summary of the literature on conflict-control loops. We then consider new theoretical challenges for conflict-control loops in multitasking, followed by empirical examples of conflict-control loops in dual-task and task-switching paradigms, as well as error monitoring and posterror adjustments in such multitasking paradigms. We conclude by outlining future research questions regarding monitoring and control in multitasking, including the potential role of affect and associative learning for conflict-control loops in multitasking.

Multitasking paradigms in cognitive psychology

Cognitive psychology has developed several tools for investigating multitasking performance (see Koch, Poljac, Müller,

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& Kiesel, 2018, for a recent review). In the laboratory context, tasks are usually defined as simple choice reaction time (RT) tasks, in which an oncoming stimulus has to be categorized according to a certain stimulus feature (e.g., is stimulus color blue or red?), and one of several response alternatives has to be chosen (e.g., pressing a left or right response key). A different categorization rule (e.g., is stimulus shape a circle or square?) would constitute a different task. Traditional dual-task paradigms compared performance in "pure" single-task blocks, in which only one stimulus occurs and hence only one task had to be performed, with blocks in which either both tasks appear in random order (but on each trial only one task is to be performed; mixed blocks) and dual-task blocks in which both stimuli are presented simultaneously and thus both tasks have to be performed together (see, e.g., Hazeltine, Teague, & Ivry, 2002; Janczyk, Nolden, & Jolicœur, 2015; Schumacher, Seymour, Glass, Kieras, & Meyer, 2001).

A further dual-task paradigm is the "overlapping tasks paradigm," which has become popular as the "psychological refractory period" (PRP) paradigm (Pashler, 1998). In the PRP paradigm, two stimuli are presented in close temporal succession but with a varying stimulus onset asynchrony (SOA). Usually, short SOAs (e.g., 50 ms) considerably slow down the response to the second stimulus, a phenomenon called "PRP effect." This effect is often interpreted as a signature of serial task processing, either as necessary requirement (Pashler, 1994) or preferred cognitive strategy (Meyer & Kieras, 1997). However, processing of the first task may also be affected by the oncoming second response in a PRP paradigm, pointing to some degree of parallel task processing (Hommel, 1998).

Apart from dual-task paradigms, task-switching paradigms have been developed to investigate rapid shifting between different cognitive tasks (Allport, Styles, & Hsieh, 1994; Meiran, 1996; Rogers & Monsell, 1995). Here, the next stimulus only occurs after the participant has responded to the first stimulus, and the two stimuli may or may not belong to different tasks. Performance costs arise when switching from one cognitive task to another, relative to performing the same task again ("task-switch costs"). Task-switch costs are thought to reflect interference from previous tasks as well as reconfiguration for the upcoming task, with varying contributions of these two kinds of processes to the overall costs (for reviews, see Kiesel et al., 2010; Monsell, 2003; Vandierendonck, Liefooghe, & Verbruggen, 2010). Different variants of the task-switching paradigm exist: Task order may be fixed or may vary randomly from trial to trial, and the upcoming task may have to be retrieved from memory or may be indicated by a task cue. Moreover, the time interval from one task to the next can vary, and task-switch costs usually decrease with longer time intervals. Also, the time interval between task cue and stimulus may vary, and longer intervals often lead to reduced task-switch costs.

One particular kind of task-switching paradigm measures the cost of switching back to a recently performed task ("*N*–2 repetition cost" or "backward inhibition"; Mayr & Keele, 2000): The more recent the previous occurrence of a particular task, the higher the cost. This measure is often interpeted as a marker of inhibitory task control (for reviews, see Gade, Schuch, Druey, & Koch, 2014; Koch, Gade, Schuch, & Philipp, 2010). Hybrids between the different multitasking paradigms have also been developed; for instance, measuring task-switch costs and *N*–2 repetition costs in a PRP paradigm in order to investigate higher-level task-order control (e.g., Hirsch, Nolden, & Koch, 2017; Kübler, Reimer, Strobach, & Schubert, 2018; Luria & Meiran, 2003; Stelzel, Kraft, Brandt, & Schubert, 2008; Strobach, Soutschek, Antonenko, Flöel, & Schubert, 2015), or to investigate action effect monitoring (Kunde, Wirth, & Janczyk, 2018; Wirth, Janczyk, & Kunde, 2018; Wirth, Steinhauser, Janczyk, Steinhauser, & Kunde, 2018).

Conflict-control loops in single tasks

Definition of conflict-control loops

The basic mechanism of cognitive control that is explored in this article can be defined as follows: The detection of cognitive conflict leads to subsequent adaptations of cognitive processing, for example, a biased processing of particular stimulus features. Botvinick and colleagues (Botvinick et al., 2001; Botvinick, Cohen, & Carter, 2004) were the first to describe this basic mechanism. Two components can be identified: (1) conflict monitoring and (2) control adjustments.

Cognitive conflict occurs whenever two or more motor (Botvinick et al., 2001) or cognitive (Holroyd, Yeung, Coles, & Cohen, 2005) representations that compete for action control are simultaneously activated. For instance, two response alternatives might be activated by an imperative stimulus in a simple RT task such as a Simon task: the imperative stimulus feature may call for a left response, but the (incongruent) stimulus location triggers a right response. Botvinick et al. (2001) suggested that the cognitive system has a "monitoring system" that constantly registers simultaneous activation of competing representations, indicating potential conflict. If conflict is detected, the conflict signal triggers a transient[1] adjustment in cognitive processing, such that, for example,

[1] Following a distinction of control on different time-scales (cf. Braver, 2012), we are referring to *transient* control in contrast to more sustained control adjustments. Whereas transient control weights the influence of the most recent events more heavily, sustained control operates on a longer time-scale and takes into account the previous learning history. Behavioral (Funes, Lupiáñez, & Humphreys, 2010) and neurophysiological (Marini, Demeter, Roberts, Chelazzi, & Woldorff, 2016) data have accrued that provide evidence for a dissociation between these control operations.

task-relevant cognitive representations are boosted (Egner & Hirsch, 2005; Nigbur, Schneider, Sommer, Dimigen, & Stürmer, 2015) and/or task-irrelevant cognitive representations are attenuated (Janczyk & Leuthold, 2018; Stürmer & Leuthold, 2003; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002). In the following discussion, we refer to this two-component process as "conflict monitoring and control adjustment" or, for the sake of brevity, the "conflict-control loop" (cf. Egner, 2008; see Fig. 1 for an illustration.)

Empirical measures of conflict-control loops

Empirical measures of the first component, conflict monitoring, mainly come from online assessments of neural activation. In the EEG, correlates of experimentally induced response conflict can be observed in the form of the N200 and N450 components (e.g., Kopp, Rist, & Mattler, 1996; Yeung, Botvinick, & Cohen, 2004). In fMRI, activation in the dorsal anterior cingulate cortex (ACC) is observed when response conflict is high (e.g., Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999). The second component, control adjustment, is on a neural level linked to the dorso-lateral prefrontal cortex (dlPFC; Egner & Hirsch, 2005; Gbadeyan, McMahon, Steinhauser, & Meinzer, 2016; Kerns et al., 2004; MacDonald, Cohen, Stenger, & Carter, 2000), which is assumed to be involved in cognitive control functions in general (e.g., Badre & D'Esposito, 2007; Cieslik et al., 2013; Koechlin & Summerfield, 2007; Miller & Cohen, 2001).

Notably, the second component can also be assessed with behavioral measures. The most popular measure is a sequential modulation of congruency effects in the Eriksen flanker task (Gratton, Coles, & Donchin, 1992), but also in other tasks, such as the Simon (e.g., Praamstra, Kleine, & Schnitzler, 1999) or Stroop (e.g., Kerns et al., 2004) tasks. In such tasks, trials can be categorized into congruent and incongruent conditions, in which the task-relevant aspect and the task-irrelevant aspect of the stimulus activate the same or different response alternatives, respectively. Performance is worse in incongruent than in congruent trials, which is usually interpreted as a measure of response conflict in incongruent trials. Gratton and colleagues first reported that this congruency effect in trial *N* is smaller after incongruent than after congruent trials in trial *N*–1, an observation that has since been replicated numerous times (see Duthoo et al., 2014a, b; Egner, 2007, 2017, for reviews), and is called the "Gratton effect" or "congruency sequence effect" (CSE). The Gratton effect was one of the effects explained by the model of Botvinick et al. (2001) and is taken as an empirical marker of a conflict-control loop: The registered response conflict triggers adjustments in subsequent stimulus processing, which in turn leads to reduced influence of the irrelevant stimulus aspect in the subsequent trial (e.g., Botvinick et al., 2001; Duthoo et al., 2014a, b; Egner, 2007, 2017). Although this reasoning has become highly influential, the interpretation of the Gratton effect as reflecting instances of cognitive control has also been critized in several respects. For instance, the critical transitions between congruency relations from a previous trial *N*–1 to the current trial *N* are often confounded with the effects of episodic retrieval (cf. Hommel, Proctor, & Vu, 2004; Mayr & Awh, 2009; Mayr, Awh, & Laurey, 2003) and contingency learning (Schmidt & De Houwer, 2011; Schmidt & Weissman, 2014). However, when controlling for such potential confounds, the Gratton effect still seems to be a valid measure of conflict-triggered control adjustment (Blais, Stefanidi, & Brewer, 2014; Egner, 2007; Kim & Cho, 2014; Ullsperger, Bylsma, & Botvinick, 2005).

Conflict-control loops in multitasking

We now turn to exploring the role of conflict-control loops in multitasking. First we will briefly review the existing literature on the task specificity versus task generality of the Gratton effect. Then we will adopt a wider perspective on conflict-control loops in multitasking, arguing that the Gratton effect describes only one of multiple possible conflict-control loops in multitasking (see Fig. 1). We argue that conflict can occur at multiple levels, including task-level conflict, and that control adjustments can take on different forms, including task-level effects.

Is the Gratton effect task-specific or task-general?

Several studies in the literature have addressed the question of whether the Gratton effect only occurs within one task or can be observed across tasks (see Braem, Abrahamse, Duthoo, & Notebaert, 2014; Egner, 2008, for reviews). That is, does experiencing a response conflict in one task (e.g., a Simon task) also affect subsequent performance in a different task (e.g., a flanker task)?

For instance, Kiesel, Kunde, and Hoffmann (2006) investigated congruency effects in a task-switching paradigm and observed a Gratton effect in task repetitions, but not in task switches, suggesting that the conflict-control loop does not generalize across task contexts (see also Kreutzfeldt, Stephan, Willmes, & Koch, 2016; Notebaert & Verguts, 2008, for similar observations). Fischer, Plessow, Kunde, and Kiesel (2010) presented Simon stimuli either alone (single-task context) or together with another stimulus (dual-task context) and observed a Gratton effect from one Simon stimulus to the next when the context remained the same, but not when the context changed.

Further evidence that Gratton effects are domain-specific has come from studies showing neural and functional dissocations between the Gratton effects in emotional and nonemotional task contexts. These studies have typically

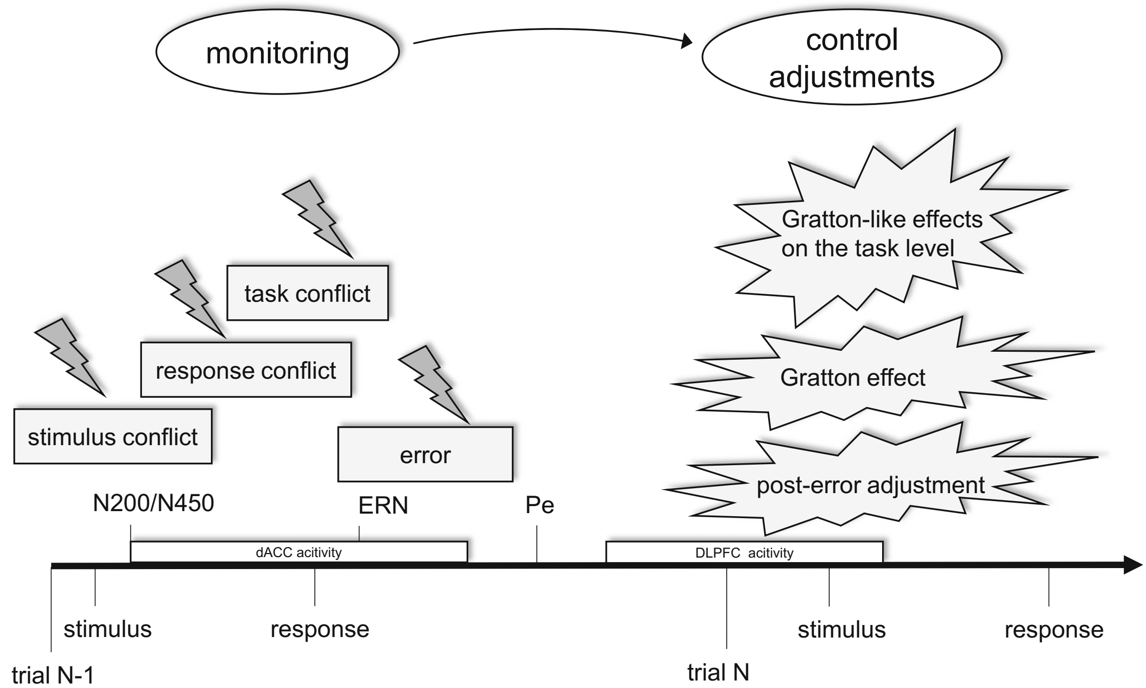

Fig. 1 Schematic overview of conflict monitoring and control adjustments in single-task and multitasking situations

compared Stroop-like tasks in which response conflict was caused by nonemotional versus emotional categories (e.g., judging the gender or emotion of faces in the context of congruent or incongruent words). Although the dlPFC was invoked only in the nonemotional task, control adjustment in the emotional task was mediated by the rostral ACC (e.g., Egner, Etkin, Gale, & Hirsch, 2008; Etkin, Egner, Peraza, Kandel, & Hirsch, 2006; Maier & di Pellegrino, 2012), a region implicated in emotional processing. Moreover, nonemotional and emotional tasks were differentially affected by dual-task demands. The Gratton effect in the nonemotional task was strongly impaired when this task was combined with a mental arithmetics task that induced working memory (WM) load (Soutschek & Schubert, 2013; Soutschek, Strobach, & Schubert, 2013). In contrast, the Gratton effect in the emotional task was decreased only when this task alternated with an emotional go/no-go task (Soutschek & Schubert, 2013). These observations suggest that, even though the conflict-control loop underlying the Gratton effect is domain-specific to some extent, it can still suffer considerably if it invokes control processes shared with other tasks.

Interestingly, Braem et al. (2014) suggested that conflict-triggered control adjustments across tasks only occur if the different task sets can be represented simultaneously in WM without interfering with each other. This might be the case when the task sets are either very similar (such that the tasks can be represented as one and the same task) or very dissimilar (such that there is no interference between the task sets). The importance of task sets for the generality of conflict-control loops has also been stressed by Hazeltine and colleagues (e.g., Akçay & Hazeltine, 2008; Hazeltine, Lightman, Schwarb, & Schumacher, 2011), who suggested that across-task control adjustments occur when participants perceive the situation as one task, but not when they perceive it as involving separate tasks.

Notably, the studies discussed so far all considered Gratton effects, assessing whether response conflict (i.e., incongruent trial) in one task does or does not trigger increased selective attention (i.e., reduced congruency effects) in a different task. Here we propose adopting a wider definition of conflict-control loops in multitasking, taking into account further levels of conflict and further kinds of control adjustments. This wider perspective entails a new set of theoretical questions, as will be discussed next.

A wider perspective of conflict-control loops in multitasking

The perspective of conflict-control loops as a general mechanism in multitasking (see Fig. 1) implicates a set of new theoretical questions: First, what kind of conflict is being monitored in multitasking? Second, what kind of control adjustments can occur in multitasking? Third, how do errors affect performance in a multitasking situation? We will now turn to each of these questions.

(1) What kind of conflict is being monitored in multitasking? We suggest that conflict monitoring is not limited to conflict at the stimulus or response level, but extends to conflict at the task level. Ideas along these lines were already

formulated by Botvinick and colleagues (Botvinick et al., 2001, 2004; see also Levin & Tzelgov, 2014): On the basis of the observation that ACC activation is not confined to situations with high response conflict, but generalizes to situations with high task conflict in a WM task (Badre & Wagner, 2004), Botvinick et al. (2004) postulated "a broader monitoring function" of the ACC (p. 542). Apart from neuroimaging observations, signatures of task conflict can also be observed on the behavioral level (e.g., Braverman & Meiran, 2015; Goldfarb & Henik, 2007; Moutsopoulou & Waszak, 2012; Steinhauser & Hübner, 2008, 2009) and on the neural level (e.g., Desmet, Fias, Hartstra, & Brass, 2011; Elchlepp, Rumball, & Lavric, 2013).

Task conflict occurs when two competing task sets are activated (e.g., "task set 1: attend to color; if blue, respond left; if red, respond right"; "task set 2: attend to shape; if circle, respond left; if square, respond right"). This is different from response conflict, which arises when two competing response alternatives are activated. Evidence that task conflict can be dissociated from response conflict empirically has come from the observation that bivalent stimuli are associated with a cost relative to univalent stimuli (e.g., Braverman & Meiran, 2015; Elchlepp et al., 2013; Goldfarb & Henik, 2007; Kalanthroff, Davelaar, Henik, Goldfarb, & Usher, 2018; Monsell, Taylor, & Murphy, 2001; Rogers & Monsell, 1995; Steinhauser & Hübner, 2008, 2009). In a task-switching situation, conflict may be induced by a stimulus feature that is irrelevant to the current task, but would be relevant in the context of the other task (bivalent stimuli; e.g., a blue square or red circle, in the above example). Performance is worse with incongruent than with congruent bivalent stimuli, indicating between-task response conflict. Notably, in task switching, performance with congruent bivalent stimuli (in which the irrelevant stimulus feature triggers the same response as the relevant feature) is often still worse than performance with univalent stimuli (in which there is no distracting stimulus feature that would be relevant to the other task). The latter observation is taken as evidence that task conflict can be dissociated from response conflict (e.g., Elchlepp et al., 2013; Rogers & Monsell, 1995; Steinhauser & Hübner, 2008, 2009). Task conflict and response conflict can be further dissociated by analyzing RT distributions. When fitting an ex-Gaussian function, task versus response conflict are mainly reflected in the exponential versus the Gaussian compononent, respectively (Steinhauser & Hübner, 2009; see also Moutsopoulou & Waszak, 2012; Shahar & Meiran, 2015). Kalanthroff et al. (2018) provided a formal computational model for the interaction of task conflict with response conflict in the Stroop task. In this model, the amount of task conflict that occurs in a particular trial depends on the current control settings of the cognitive system: The stronger the a priori activation of the relevant task representation, the less task conflict occurs.

(2) What kind of control adjustments can occur in multitasking? In a single-task context, a strong processing bias has been postulated, such as stronger activation of the task-relevant stimulus dimension and/or stronger inhibition of the irrelevant stimulus dimension (Botvinick et al., 2001). In a multitasking context, such increased top-down biasing can occur within tasks just as in single-task contexts, but it can also occur across tasks, affecting task-switching performance. Although the Gratton effect usually does not transfer from one task to the next (see the previous section), other across-task control adjustments have been reported. For instance, Goschke (2000) observed that switching to a new task is more difficult after an incongruent trial (i.e., after between-task response conflict) than after a congruent trial (i.e., no between-task response conflict). This can be explained by assuming that the response conflict triggers control adjustments, such as stronger activation of the relevant task representation and/or stronger inhibition of the competing task representation, which impairs performance in the case of a subsequent task switch (Goschke, 2000; see Brown, Reynolds, & Braver, 2007, for a computational model of this effect).

Brown et al. (2007) identified another conflict-control loop in task switching: Trial-to-trial changes such as task switches or response switches trigger a shift in the speed–accuracy trade-off toward slower and more accurate responding in the subsequent trial; this shift lasts over the course of several trials. That is, the detection of task conflict or response conflict triggers control adjustments, in the form of general slowing and higher accuracy. In a similar vein, in their model of the Stroop task, Kalanthroff et al. (2018) suggested that the detection of task conflict triggers a shift of response threshold toward slower responding (see also Meier & Rey-Mermet, 2012; Rey-Mermet & Meier, 2012).

Beyond adjustments of processing bias and speed–accuracy trade-off, other control adjustments are possible. For instance, if participants have some degree of control over task choice, they can withdraw from conflict-associated tasks and choose alternative tasks (cf. Botvinick, 2007). Here, the idea is that conflict acts as a teaching signal at the level of task representations and biases choice away from conflict-associated tasks (cf. Dignath, Kiesel, & Eder, 2015).

(3) How do errors affect performance in a multitasking situation? In a single-task context, error monitoring and posterror adjustments have been suggested to be another instance of conflict detection and control adjustment.

Table 1 Summary of types of conflict-control loops under multitasking adressed in the review of empirical findings

Phenomenon	Conflict	Control Adjustment
Sequential backward crosstalk effect	Between-task response conflict	Task shielding (i.e., stronger biasing of task-relevant vs. -irrelevant features) or suppression of the other task's activation
N–2 task repetition cost	Task conflict	Task inhibition
After effect of *N*-2 task repetition	Task conflict	More efficient task processing
Conflict avoidance effect	Within-task response conflict	Task selection (bias away from conflict-related task)
Error aftereffects in dual task	Postresponse conflict	Adaptive shift in speed–accuracy trade-off (specific to same subtask)

Extending this reasoning to multitasking, the following challenges emerge: What kind of errors are being monitored in multitasking? For instance, can within-task errors (i.e., selecting the wrong response) be distinguished from between-task errors (i.e., selecting the wrong task)? Furthermore, what kind of posterror adjustments can occur in multitasking? Errors have been shown to elicit not only adaptive adjustments that improve subsequent behavior, but also nonadaptive adjustments—that is, performance decrements elicited by error processing or the learning of errors.

In the next section, we will review a number of recent empirical results from the task-switching and dual-task literature that can be viewed as conflict-control loops in multitasking under this wider perspective. We propose that this perspective facilitates integration of these different findings into a common theoretical framework.

A selective review of empirical findings

In our selective review, we focus on four sets of empirical phenomena in the dual-task and task-switching literature that may be regarded as conflict-control loops in multitasking (see Table 1): the sequential backward crosstalk effect in dual tasks, sequential effects of trials *N*–2 and *N*–3 in task switching, the conflict avoidance effect in voluntary task switching, and several empirical phenomena related to error monitoring and posterror adjustments in multitasking. These examples involve different levels of conflict as well as different kinds of control adjustments (see Table 1 for an overview), illustrating our general theoretical perspective. Our selective review is by no means exhaustive, and we expect that further empirical multitasking phenomena will be integrated into this perspective in future research.

The sequential backward crosstalk effect in dual tasks

The first example concerns between-task response conflict in a dual-task situation. In dual-task situations, participants often work on two time-overlapping tasks requiring different responses to the different tasks, and congruency relations (also called *compatibility relations*) can arise between the stimuli and responses of both tasks. One example is the compatibility-based backward crosstalk effect (BCE; Hommel, 1998; see also Ellenbogen & Meiran, 2008; Hommel & Eglau, 2002; Janczyk, Pfister, Hommel, & Kunde, 2014; Janczyk, Renas, & Durst, 2018; Lien & Proctor, 2000; Naefgen, Caissie, & Janczyk, 2017; Watter & Logan, 2006; for other types of BCEs, see, e.g., Durst & Janczyk, 2018; Miller, 2006). In a typical experiment, a colored letter serves as the stimulus. Task 1 is giving a left/right manual response (R1) to the letter identity, and Task 2 is giving a left/right vocal or pedal response (R2) to the letter color. The important result is that even Task 1 RTs are shorter in R1-R2-compatible trials (e.g., left manual and left pedal response) than in R1-R2-incompatible trials (e.g., left manual but right pedal response). This BCE may be conceived of as a between-task congruency effect, with both stimulus features being relevant for successful performance of the dual-task pair.

The BCE can, of course, also be investigated as a function of the R1–R2 compatibiliy relation not only in the current trial *N*, but also in the previous trial *N*–1. Like the Gratton effect, the BCE exhibits a large sequential modulation when this is done (Janczyk, 2016; see also Scherbaum, Gottschalk, Dshemuchadse, & Fischer, 2015): A large BCE (with manual and pedal responses) was visible following R1-R2-compatible trials, but the BCE was absent (or even reversed) following R1-R2-incompatible trials (see Fig. 2). This sequential modulation also occurs with vocal responses in Task 1 or Task 2 (Renas, Durst, & Janczyk, 2017) and has been reported for preschool children (Janczyk, Büschelberger, & Herbort, 2017) as well as for older adults (Janczyk, Mittelstädt, & Wienrich, 2018).

Smaller BCEs have previously been interpreted as an index of more efficient "task shielding" (Fischer, Gottschalk, & Dreisbach, 2014; Fischer & Hommel, 2012; Scherbaum et al., 2015), and the small/absent BCE following R1-R2-incompatible trials can thus be taken to indicate adjustments in such task shielding as a consequence of just-experienced R1–R2 conflict. Although the exact mechanisms of such task shielding are vague and remain to be elucidated, one may also speculate that following R1-R2-incompatible trials, any Task

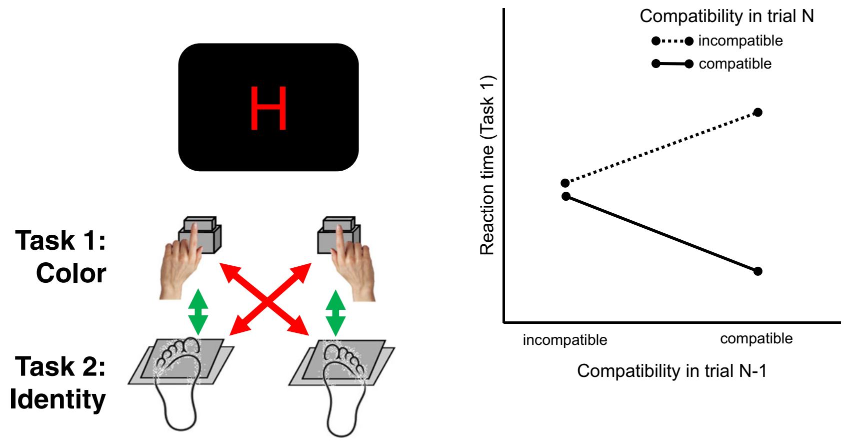

Fig. 2 Conflict-control loops across dual-task pairs. (Left) Schematic illustration. If both responses are given on the same side, they are considered R1–R2 compatible (green arrows), otherwise they are R1–R2 incompatible (red arrows). (Right) Empirical signature of conflict adaptation in this situation. First, the RTs in Task 1 (the manual color task, in the figure) are shorter in compatible trials (the compatibility-based backward crosstalk effect, or BCE). Second, this BCE is larger following compatible trials *N*–1 than following incompatible trials *N*–1, thus showing a sequential modulation similar to the Gratton effect (see, e.g., Janczyk, 2016, for an empirical example)

2 response activation is suppressed and thus cannot interfere with Task 1 response selection.

To account for this BCE in the framework of Pashler's (1994) central bottleneck model, it was suggested that the capacity-limited stage of response selection is preceded by a capacity-unlimited stage of response activation (e.g., Hommel, 1998; Lien & Proctor, 2002; see also Schubert, Fischer, & Stelzel, 2008). Because response activation can occur in parallel in two tasks, crosstalk between the tasks can arise. In two recent studies, however, the source of the BCE was identified directly within the capacity-limited stage of processing (Janczyk, Renas, et al., 2018; Thomson, Danis, & Watter, 2015).

The stimulus used in such experiments would count as "bivalent" in the context of task switching. This, in turn, might give rise to effects that would be interpreted as indicators of task-level conflict in the task-switching literature (see Kiesel et al., 2010; Koch et al., 2018, for reviews). In the absence of evidence for this, and particularly against the background of those studies that have located the compatibiliy-based BCE in the response selection stage, a more parsimonious possibility is that the compatibility-based BCE represents a special case of a flanker effect: The stimulus dimension for Task 2 automatically activates a response feature in much the same way the flankers do in a flanker task. This activation is added to the activation resulting from the "intentional" response selection ongoing in Task 1 (see Ulrich, Schröter, Leuthold, & Birngruber, 2015) and speeds Task 1 RTs in compatible trials, but also slows down Task 1 RTs in incompatible trials. Even though there are of course differences between a flanker task and the BCE task (e.g., the flankers are task-irrelevant, whereas the second stimulus feature in a BCE task is clearly task-relevant), the same mechanisms of conflict monitoring and control adjustment may be at work in both cases. As such, an effect that occurs in the context of dual-tasking might in fact be explained by mechanisms suggested in the context of single tasks.

Sequential effects in task switching: effects of N–2 and N–3

The second example illustrates how task-level conflict can trigger control adjustments in a task-switching situation. This example focuses on *N*–2 task repetition costs, which are a special kind of task-switch costs and are usually interpreted as a measure of task-level inhibition ("backward inhibition"; Mayr & Keele, 2000; see Gade et al., 2014; Koch et al., 2010, for reviews). *N*–2 task repetition costs are computed as the performance difference in task-switching sequences of types ABA (*N*–2 task repetition) and CBA (*N*–2 task switch), where performance is usually worse in ABA than in CBA sequences. To account for this observation, it is assumed that during the switch from Task A (in trial *N*–2) to Task B (in trial *N*–1), the no-longer-relevant Task A becomes inhibited in order to avoid interference. When a participant immediately returns to this Task A (in trial *N*) in an ABA sequence, more persisting inhibition needs to be overcome than when returning to this task after two or more intermediate trials, as in a CBA sequence. Of note, *N*–2 task repetition costs constitute a task-level effect: They occur regardless of the specific stimulus or response in the task episodes of trials *N*–2 and *N*, and cannot be reduced to interference on the stimulus or response level (Mayr & Keele, 2000; see also Grange, Kowalczyk, & O'Loughlin, 2017; for reviews, see Gade et al., 2014; Koch et al., 2010).

Here we suggest that the *N*–2 task repetition cost can be conceived of as conflict monitoring and adjustment on the task level: During the switch from trial *N*–2 to trial *N*–1, a task conflict is detected, and the detection of this conflict leads to a control adjustment in the form of inhibition of the no-longer-relevant task. Such monitoring and adjustment at the task level is formalized in the connectionist model by Sexton and Cooper (2017). Following previous computational accounts (Brown et al., 2007), this model combines the task-switching model of Gilbert and Shallice (2002) and the conflict-monitoring model of Botvinick et al. (2001). Similar to the latter model, a conflict-monitoring layer detects conflict between competing representations, but rather than conflict between competing response alternatives, here conflict at the level of competing task representations is being monitored in Sexton and Cooper's model.

Furthermore, there is first evidence for another mechanism of conflict monitoring and adjustment at the task level: Schuch and Grange (2015) suggested that in trial *N* of ABA sequences, in which Task A becomes relevant again, the persisting inhibition of Task A constitutes another task conflict. Detection of this task conflict, in turn, may lead to increased cognitive control in the subsequent trial. In line with this idea, Schuch and Grange (2015) reported that in an *N*+1 trial *after* an ABA task sequence, performance is improved (i.e., shorter RTs) than in an *N*+1 trial after a CBA task sequence (see Fig. 3 for an illustration), and they interpreted this observation as resulting from control adjustments. The exact cognitive processes involved in this case, however, still need to be investigated further. One candidate for such control adjustment is improved preparation for the upcoming task (but first empirical evidence speaks against this possibility; Schuch & Grange, 2018).

To summarize, by extending conflict monitoring from the response level to the task level, the sequential task effect described by Schuch and Grange (2015) might be described as a "Gratton-like effect on the task level." Next we will turn to different kinds of consequences that can be triggered by the detection of conflict. Apart from compensatory adjustments, there might be changes in task selection preferences, as will be outlined below.

The conflict avoidance effect in voluntary task switching

The third example illustrates another kind of control adjustment, one that occurs when participants are able to voluntarily select the upcoming task. Previous research has studied the ability to adjust performance to conflict independently from the ability to voluntarily select tasks. However, in most of our day-to-day multitasking routines, we rely on hierarchies of actions that require us to do both (Miller, Galanter, & Pribram, 1960): We have to decide which task to perform and subsequently to execute the selected task. In an attempt to integrate both aspects, a multitasking paradigm was developed that measures the impact of conflict on task choices and task performance simultaneously (Dignath et al., 2015). Participants choose at the start of each trial, with their left hand, whether they want to perform a flanker or a Simon task; stimuli of the selected task then appear after task selection, and participants perform the task with their right hand. In contrast to previous research that manipulated conflict frequency (e.g., Kool, McGuire, Rosen, & Botvinick, 2010), we controlled for the influence of more recent trial history and presented congruent and incongruent trials equally often (as has been the case for other studies that have investigated transient control adjustments like the Gratton effect). Therefore, participants could not learn to base their choices on expectancies of conflict. Two important results were revealed in this study: First, participants showed a Gratton effect in task performance for task repetitions, but not for task switches. This is in line with studies showing that conflict-triggered control adjustments are task-specific (see the section above on the Gratton effect). Second, participants showed increased switch rates following conflict in the previous trial *N*–1. This *conflict avoidance effect* shows that participants' task choices are biased away from the task that was previously associated with conflict (Dignath et al., 2015; see Fig. 4).

One interpretation of this conflict avoidance bias proposes that conflict during task performance elicits a negative affective response (Dreisbach & Fischer, 2012a; for a review, see Saunders, Lin, Milyavskaya, & Inzlicht, 2017) that triggers a motivational tendency to avoid the source of conflict (Dignath & Eder, 2015). Such a transient avoidance response is in line with research on more sustained conflict avoidance (Kool et al., 2010; Schouppe, Demanet, Boehler, Ridderinkhof, & Notebaert, 2014; Desender, Calderon, Van Opstal, & Van den Bussche, 2017). Here, participants have to choose between two tasks that are associated with different conflict frequencies. The results of such studies have shown that participants gradually learn to avoid high-conflict tasks and prefer low-conflict tasks.

Theoretically, this influence of conflict on task choices can be explained by a recent extension of the conflict-monitoring theory (Botvinick, 2007). According to this proposal, conflict acts as a negative affective signal that is used to inform two mechanisms of control adjustment. On the one hand, conflict triggers control adaptation in terms of the Gratton effect in task performance. On the other hand, conflict acts as a teaching signal that biases task selection away from effortful, conflict-related tasks (Botvinick, 2007; Dignath et al., 2015).

Error monitoring and posterror adjustments in multitasking

In this final empirical section, we review a number of phenomena related to error processing in multitasking, which constitutes a further example of conflict-control loops. Whereas errors in single-tasking situations are typically mere

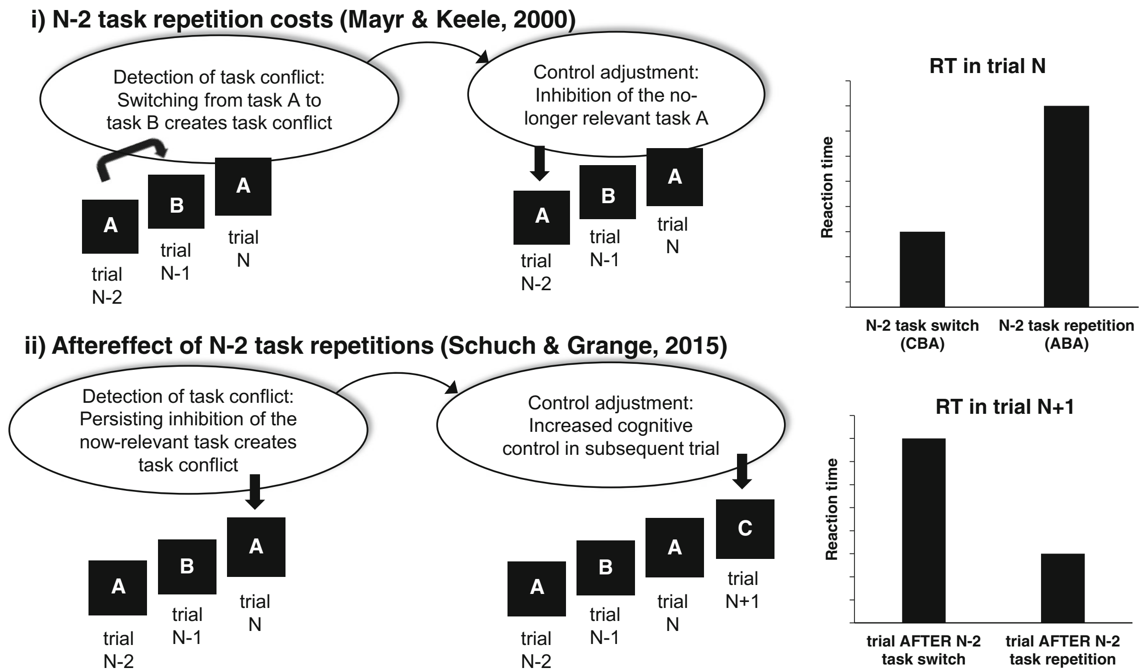

Fig. 3 Conflict-control loops at the task level. (Left) Schematic illustration. (Right) Empirical measures of control adjustments at the task level. Inhibition of a no-longer-relevant task can be measured indirectly by comparing trials in which participants return to the previously inhibited task after one intermediate trial (*N*–2 task repetitions, with more persisting inhibition) or after two or more intermediate trials (*N*–2 task switches, with less persisting inhibition). Increased cognitive control after an *N*–2 task repetition can be measured by comparing performance in the trials *after N*–2 task repetitions and *after N*–2 task switches. Both of these effects can be found with different task-switching paradigms, such as perceptual classification tasks (Mayr & Keele, 2000; Schuch & Grange, 2015) or face classification tasks (Schuch & Grange, 2015, 2018)

response confusions, multitasking can additionally lead to errors due to the application of the incorrect task, so-called *task confusions*. In both single-task and multitasking situations, these errors are caused by conflict on different levels. It is therefore tempting to assume that the adjustments described above treat errors and conflicts in comparable ways. However, theoretical concepts and empirical observations from research on conflict cannot easily be extended to errors, for several reasons: First, error monitoring involves not only the detection of errors but also the evaluation of the type and significance of errors. Second, error detection is typically accompanied by an immediate conscious experience of having made an error. Finally, errors can not only lead to adaptive adjustments but can also have detrimental effects on subsequent behavior. In the following discussion, we provide an overview of the specific implications and challenges of error monitoring and posterror adjustments under multitasking conditions.

In recent years, research on error monitoring has focused on two types of error-related brain activity in event-related potentials: the error-related negativity (ERN or Ne; Falkenstein, Hohnsbein, Hoormann, & Blanke, 1990; Gehring, Goss, Coles, Meyer, & Donchin, 1993), a frontocentral negativity

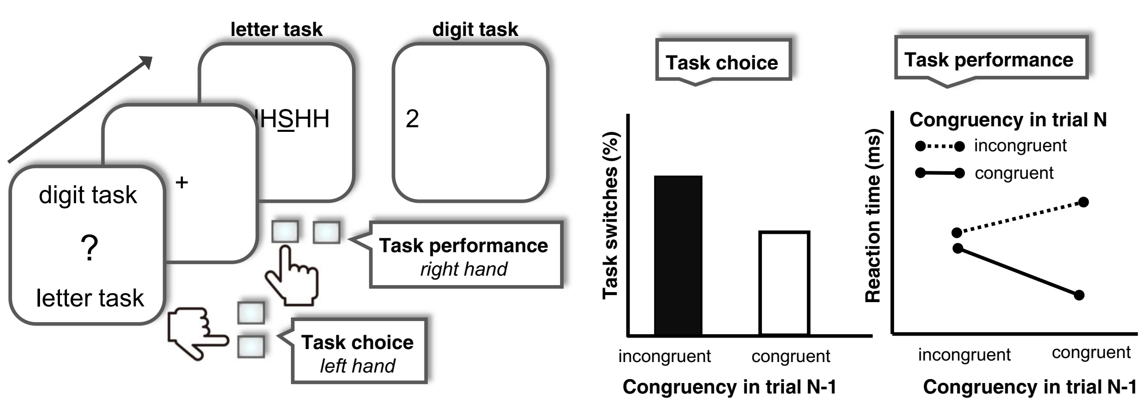

Fig. 4 Conflict avoidance in multitasking. (Left) Schematic illustration. Participants first choose between a flanker ("letter") task and a Simon ("digit") task with their left hand; subsequently, they perform the selected task with their right hand. (Right) Empirical measures of conflict avoidance for task choices (increased switch rate for previously incongruent trials) and conflict adjustment for task performance (the Gratton effect for task repetitions; see, e.g., Dignath et al., 2015, for an empirical example)

that occurs within 100 ms after an error, and the error positivity (Pe; Falkenstein et al., 1990), a posterior positivity peaking between 250 and 350 ms after the error. Because the ERN shares a neural generator with the conflict-related N200 (i.e., the dorsal ACC), conflict-monitoring theory has attributed the ERN to postresponse conflict between the error response and a corrective response tendency, which serves as the basis of error detection (Yeung et al., 2004). In contrast, alternative accounts have interpreted the ERN as a (reward) prediction error (Alexander & Brown, 2011; Holroyd & Coles, 2002) or a signal carrying information about the type and significance of errors (Hajcak, Moser, Yeung, & Simons, 2005; Maier & Steinhauser, 2013). These explanations are not mutually exclusive, as recent studies have proposed that the ERN is based on multiple neural generators implicated in both conflict and value representation in the brain (Bonini et al., 2014; Buzzell, Richards, et al., 2017). Although the mechanisms underlying the ERN are still under debate, the later-appearing Pe has rather consistently been viewed as a correlate of error awareness (Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001) or response confidence (Boldt & Yeung, 2015), presumably emerging from a decision process that conceptually resembles a response selection process (Steinhauser & Yeung, 2010). Thus, whereas error and conflict monitoring might be based on partially similar monitoring processes, error processing involves additional mechanisms related to the evaluation and conscious detection of errors.

Multitasking situations create a number of specific challenges for the detection and evaluation of errors. Regarding the monitoring component, error monitoring might rely on resources that are depleted if multiple tasks are held in WM, thus impairing some or all of the monitoring mechanisms involved. Several studies have measured error-related brain activity in a flanker task when it is combined with WM tasks that produce variable WM load. First, Klawohn, Endrass, Preuss, Riesel, and Kathmann (2016) observed a reduced ERN under these conditions in healthy participants (but not in patients with obsessive compulsive disorder). Second, Maier and Steinhauser (2017) used a flanker paradigm in which the contributions of error detection and error evaluation to the ERN could be separated, and they observed that high WM load led to impaired error evaluation but preserved error detection. Finally, Moser, Moran, Schroder, Donnellan, and Yeung (2013) reported that the ERN was even increased under high WM load, and they explained this effect by a compensatory increase of monitoring effort. These heterogeneous results might reflect differences in task parameters and load manipulations across studies, but they still demonstrate that multitasking impacts basic error-monitoring functions. It appears surprising that none of these studies have reported an effect on the Pe. This could reflect the fact that none of these studies have involved a temporal overlap between error monitoring in the flanker task and the decision stages of the WM task. Indeed, in another study (Weißbecker-Klaus, Ullsperger, Freude, & Schapkin, 2016) the researchers observed a reduced Pe when a flanker task was the first task in a PRP paradigm, relative to a single-task condition.[2] This suggests that the decision stages of concurrent tasks can interfere with conscious error processing when both overlap in time.

Also the behavioral consequences of errors are (still) more multifaceted than the adjustments observed after conflict. Errors have been shown to affect subsequent behavior in two fundamentally different ways (Danielmeier & Ullsperger, 2011). On the one hand, errors can trigger adaptive adjustments of attention and behavior that serve to prevent further errors. Increased RTs following errors (posterror slowing) have frequently been interpreted as a strategy shift toward more cautious responding (Botvinick et al., 2001; Dutilh et al., 2011). Moreover, numerous studies have reported improved attention and task-related activity on posterror trials (Danielmeier, Eichele, Forstmann, Tittgemeyer, & Ullsperger, 2011; King, Korb, von Cramon, & Ullsperger, 2010), effects that appear to be sensitive to the type of error (Maier, Yeung, & Steinhauser, 2011; Steinhauser & Kiesel, 2011). On the other hand, errors can induce performance decrements on subsequent trials, often called *nonadaptive adjustments*. Posterror slowing has alternatively been interpreted as a nonadaptive orienting response to an infrequent event (Houtman & Notebaert, 2013; Notebaert et al., 2009) or a bottleneck induced by error monitoring (Jentzsch & Dudschig, 2009). These views have received support from studies showing impaired performance and attentional decrements on posterror trials (Purcell & Kiani, 2016; van der Borght, Schevernels, Burle, & Notebaert, 2016), particularly when the interval between an error and the subsequent stimulus is short (Buzzell, Beatty, Paquette, Roberts, & McDonald, 2017; Jentzsch & Dudschig, 2009; van der Borght, Braem, Stevens, & Notebaert, 2016).

Given that error monitoring is impaired under multitasking, one might expect that adaptive posterror adjustments would also be less pronounced under multitasking. However, whereas posterror slowing was indeed absent under multitasking in one study (Weißbecker-Klaus et al., 2016), Steinhauser, Ernst, and Ibald (2017) recently showed that both adaptive and nonadaptive posterror adjustments can be identified in a PRP paradigm. They combined an error-prone flanker task as Task 1 with an auditory pitch discrimination as Task 2 and investigated the effects of Task 1 errors on subsequent behavior. Task 1 errors impaired Task 2 performance on the same trial, and this detrimental effect was larger with a smaller stimulus onset asynchrony (see also Lavro & Berger, 2015). At the same

[2] A similar effect was evident in a study with fully overlapping tasks (Pailing & Segalowitz, 2004), although the Pe was not statistically analyzed in that article. In contrast to Weißbecker-Klaus et al. (2016), this study also reported a reduced Ne/ERN under dual-tasking.

time, however, Task 1 errors induced adaptive posterror slowing, indicative of a criterion shift on Task 1 but not Task 2, across several subsequent trials (see Fig. 5). This pattern not only shows that adaptive and nonadaptive posterror adjustments coexist and can be elicited by the same error, it also indicates that adaptive posterror adjustments under multitasking are subtask-specific (see also Forster & Cho, 2014). This implies that the underlying error-monitoring system is able to validly assign an error signal (e.g., postresponse conflict) to the task that caused the error.

Although the aforementioned studies conceptualized errors as incorrect responses in individual subtasks, multitasking can also lead to errors due to the application of the incorrect task. These task confusions were mainly investigated in task-switching paradigms in which multiple tasks can be applied to a given stimulus. Whereas some of these studies have simply assumed that errors on incongruent stimuli are predominantly task confusions (e.g., Ikeda & Hasegawa, 2011), other studies have developed methods to separate task confusions from response confusions. First, Meiran and Daichman (2005) assigned each hand to one task, and considered responses with the incorrect hand to be task confusions. Second, Steinhauser and Gade (2015) used two three-choice tasks with always-incongruent stimuli, and they considered responses to the irrelevant stimulus element to be task confusions but all remaining error responses to be response confusions. Using these methods, it could be shown that task confusions can result from insufficient preparation (Meiran & Daichman, 2005; Steinhauser, Maier, & Ernst, 2017), as well as from stimulus-induced task conflict (Steinhauser & Gade, 2015). As compared to simple response confusions, task confusions are associated with activity in more frontal brain areas (Desmet et al., 2011) and a reduced ERN (Ikeda & Hasegawa, 2011; Steinhauser, Maier, & Ernst, 2017; but see Schroder, Moran, Moser, & Altmann, 2012). The latter result might come about because the corrective response tendency underlying postresponse conflict is weaker if no stable task set is adopted (Steinhauser, Maier, & Ernst, 2017). Regarding posterror adjustments, task confusions lead to a specific form of nonadaptive adjustment, so-called *switch benefits* (Desmet, Fias, & Brass, 2012; Steinhauser & Hübner, 2006). Application of an incorrect task leads to the strengthening of this task, thus leading to benefits if the subsequent trial requires a switch to this erroneously applied task. This form of error learning occurs even if the error is detected (Steinhauser & Hübner, 2006) and can be compensated for only by an immediate overt correction response (Steinhauser, 2010) or an adaptive compensatory adjustment (Steinhauser & Hübner, 2008). Little is known about how error monitoring deals with task confusions in situations with overlapping task performance (such as in the PRP paradigm), but it is plausible to assume that detecting and preventing the negative consequences of task confusions is a major goal of the control processes involved in multitasking situations.

Summary and future research questions

The perspective that conflict-control loops of various sorts play a role in multitasking allows for the integration of several empirical phenomena in the cognitive control literature. Below, we summarize the observations reviewed above and then outline outstanding questions that may guide future research.

What is being monitored?

As we reviewed in the above examples, conflict monitoring may occur at different levels: These include the level of response conflict as it occurs with flanker and Simon stimuli, in which task-relevant and task-irrelevant stimulus dimensions evoke competing response alternatives. A (perhaps) different kind of response conflict occurs in dual-task and task-switching settings, in which again task-relevant and task-irrelevant stimulus dimensions evoke competing response alternatives. However, other than in single-task contexts, the currently task-irrelevant stimulus dimension might become relevant in the next moment, when switching to the other task in a dual-task pair or task-switching setting (Janczyk, 2016; Janczyk, Renas, et al., 2018; Kiesel et al., 2006). Beyond response conflict, conflict monitoring may also occur at the level of tasks (Schuch & Grange, 2015, 2018; Sexton & Cooper, 2017). Task conflict can be elicited by the persisting activation of a previous task set or persisting inhibition of the relevant task set. Such task conflict may be increased if a currently task-irrelevant stimulus dimension triggers activation of a competing task in a bottom-up fashion (e.g., Allport & Wylie, 1999, 2000; Koch & Allport, 2006; Waszak, Hommel, & Allport, 2003). Moreover, beyond the response and task levels, conflict monitoring may occur at the level of postresponse conflict, where it serves as an indicator for the occurrence of errors (Yeung et al., 2004) and may support the detection of errors in individual subtasks under multitasking (Steinhauser, Maier, & Ernst, 2017).

Possibly, further levels may be identified; for instance, stimulus conflict might constitute another level that can be distinguished from response conflict. In a single-task flanker paradigm, Verbruggen, Notebaert, Liefooghe, and Vandierendonck (2006) dissociated response conflict (when the flankers activated a competing response) and stimulus conflict (when the flankers activated the same response as the target, but were not identical to the target). These authors observed a Gratton effect on the level of stimulus conflict, suggesting that stimulus conflict might constitute a separate level of conflict monitoring. Future research will need to

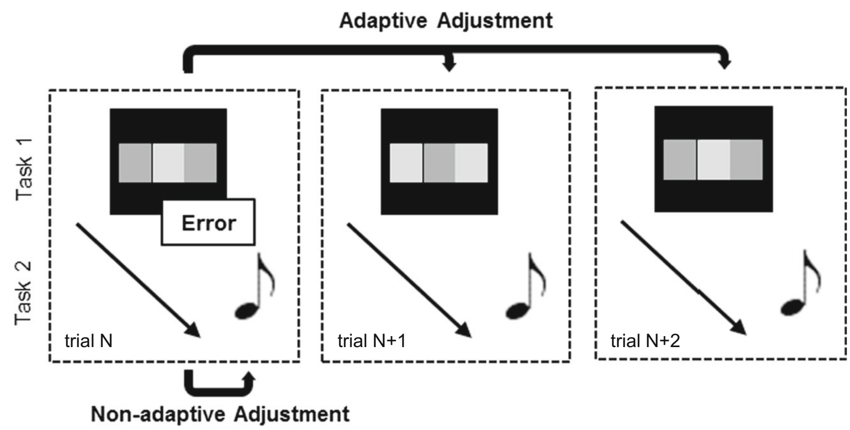

Fig. 5 Posterror adjustments elicited by a Task 1 error in the psychological refractory period paradigm of Steinhauser, Ernst, et al. (2017). Task 1 is a visual–manual color flanker task in which the color of the central square has to be classified. Task 2 is an auditory–manual pitch discrimination task. Task 1 errors elicit nonadaptive adjustments (interference) in Task 2 of the same trial, but adaptive adjustments (criterion shifts) in Task 1 across several subsequent trials

extend this finding to a multitasking context, in which perhaps several levels of stimulus conflict can be distinguished, depending on the task.

Another open question to date is whether, and how, these different levels of monitoring may interact. In the aforementioned model by Brown et al. (2007), two distinct conflict-monitoring modules were implemented: one module monitoring for response conflict (within-trial), and one module monitoring for change-related conflict (i.e., changes in task or response across trials). The two modules trigger different kinds of control adjustments, with the former triggering a stronger processing bias in favor of task-relevant as opposed to task-irrelevant features, and the latter triggering an overall reduction of response-related activity, leading to overall slowing in responding. In a similar vein, Egner (2008) argued for multiple independent conflict-control loops in the cognitive system.

What kinds of control adjustment?

The examples reviewed above involved control adjustments of several kinds: Janczyk and colleagues observed a Gratton-like sequential modulation in a dual-task paradigm, in the form of reduced BCEs in dual-task pairs after R1-R2-incompatible relative to -compatible dual-task pairs (Janczyk, 2016; Janczyk et al., 2017; Janczyk, Mittelstädt, et al., 2018; Renas et al., 2017). Schuch and colleagues observed that control adjustments at the task level involve inhibition of the no-longer-relevant task during a task switch (Sexton & Cooper, 2017), as well as improved performance after task conflict (Schuch & Grange, 2015). Dignath and colleagues reported that the experience of response conflict triggered conflict avoidance, as observed in biased task selection when participants were given the opportunity to freely choose the upcoming task in a task-switching setting (Dignath et al., 2015). Finally, the examples included instances of both adaptive and nonadaptive adjustments following errors in a multitasking setting. Steinhauser, Ernst, et al. (2017) reported task-specific control adjustments, such as strategy shifts, as well as task-unspecific interference, in the form of error monitoring interfering with subsequent task processing.

As with the different levels of monitoring, the question arises whether, and how, the different kinds of control adjustments may interact, an issue that needs to be addressed in future research. Also, it will be worth investigating to what extent the control adjustments in multitasking could be boiled down to the same mechanisms that are invoked in single-task control adjustments. We note that a multitasking context involves new theoretical questions. One issue specific to multitasking is the "credit assignment problem": For task-specific control adjustments to occur, the cognitive system needs to determine which task caused a given conflict signal in a multitasking situation. Another issue is the "optimizing of multitasking performance." Successful multitasking might be achieved by optimizing each task, through maximally separating the processing of different concurrent tasks. Alternatively, successful multitasking could be achieved through optimizing overall performance, by allowing parallel processing of the different tasks as far as possible. For example, Reissland and Manzey (2016) provided a preview of the stimuli required for the upcoming task and demonstrated that at least some participants actually processed the perceptual information while they were still busy with another task. Depending on the optimization strategy, across-task control adjustments may or may not be useful. Future research should focus on these issues.

Conflict monitoring as affective monitoring?

An aspect only briefly discussed so far concerns the affective dimension of conflict. We have seen above that emotional stimuli can elicit conflict that is resolved by emotion-specific control loops (e.g., Egner et al., 2008; Etkin et al., 2006; Maier & di Pellegrino, 2012). Importantly, there is considerable evidence that negative affect also plays a crucial role in conflict-control loops in nonemotional task contexts.

First, conflict and errors trigger negative affect. The negative affective valence of errors (e.g., Aarts, De Houwer, & Pourtois, 2012, 2013) and of stimulus and response conflict has been demonstrated in several studies (e.g., Braem et al., 2017; Brouillet, Ferrier, Grosselin, & Brouillet, 2011; Dignath & Eder, 2015; Dreisbach & Fischer, 2012a; Fritz & Dreisbach, 2013) and is discussed in several reviews (Botvinick, 2007; Dreisbach & Fischer, 2015, 2016; Inzlicht, Bartholow, & Hirsh, 2015; Saunders et al., 2017; van Steenbergen, 2015).

Second, negative affect modulates control adjustments. For instance, a negative affective state increases the Gratton effect in a single-task context (e.g., Schuch & Koch, 2015; Schuch, Zweerings, Hirsch, & Koch, 2017; van Steenbergen, Band, & Hommel, 2010). Moreover, a negative affective state is associated with increased error monitoring, as indexed by an increased ERN in the EEG (e.g., Inzlicht & Al-Khindi, 2012; Olvet & Hacjak, 2012; Wiswede, Münte, & Rüsseler, 2009; Wiswede, Münte, Goschke, & Rüsseler, 2009; but see Cano Rodilla, Beauducel, & Leue, 2016). Affective modulations of the Gratton effect are also observed when the affective context is manipulated on a trial-by-trial basis, by inserting affective stimuli in between trials. However, this approach has yielded rather mixed results, with some studies showing an increased Gratton effect following positive stimuli (van Steenbergen, Band, & Hommel, 2009; Zeng et al., 2017); other studies reporting a decreased Gratton effect following positive stimuli (Padmala, Bauer, & Pessoa, 2011); and some studies reporting no influence of affective stimuli on the Gratton effect (Dignath, Janczyk, & Eder, 2017; Stürmer, Nigbur, Schacht, & Sommer, 2011).[3]

Given that negative affect is inherent to conflict and that a negative affective state is associated with increased control adjustments, negative affect may act as a "common currency" for conflict monitoring and control adjustments. In this sense, conflict-control loops could be understood as an emotional process, as has been proposed by Inzlicht et al. (2015).

Notably, the above-mentioned studies all applied single-task paradigms, and little is known about the role of affect for conflict-control loops in multitasking. In a recent study, Schuch and Pütz (2018) manipulated affective state in a task-switching paradigm and assessed the Gratton effect both within and across tasks. They observed a double dissociation, with within-task control adjustments being increased under negative affect, but across-task control adjustments being increased under positive affect. In a similar vein, Braem et al. (2013) investigated affective modulations of the typical observation of larger task-switch costs after incongruent than after congruent trials (Goschke, 2000). They reported this effect (which also constitutes an across-task control adjustment) to be increased in a positive (vs. negative) affective context, but only in a purely affective context. When the affective stimuli were performance-contingent, and hence the positive stimuli acted as a reward signal, the data pattern was reversed. These studies suggest that affective modulations in a multitasking context are multifaceted.

To sum up, regarding the present perspective of multitasking involving several conflict-control loops at different levels of cognitive representations, affect might be a "common currency" underlying all these conflict-control loops. In single-task contexts, negative affect might be the common link between conflict detection and control adjustment, with conflict triggering negative affect, which in turn signals the need for control adjustments. In multitasking contexts, negative and positive affect might have dissociable influences on within- and between-task control adjustments. Yet it seems clear that further research will be needed to fully understand the role of affect for conflict-control loops in multitasking.

Conflict-control loops as associative learning?

An interesting perspective is to view conflict-control loops as an instance of associative learning (Abrahamse, Braem, Notebaert, & Verguts, 2016; Egner, 2014; Verguts & Notebaert, 2009). The general idea of feature-binding accounts is that all cognitive representations that are activated in a certain moment (i.e., in one particular trial) are integrated into an "episode" or "event file" (see Hommel, 1998; Hommel et al., 2004). If any of these features is present on the subsequent trial, the whole episode will be retrieved. This leads to facilitated or impaired processing if the subsequent trial involves the same or a different episodic feature, respectively.

Whereas earlier accounts assumed that the episode file contains features referring to the external situation (e.g., blue color of stimulus, left button press, etc.), Egner (2014) suggested that features of the internal situation of the cognitive system (e.g., the current task set, the current attentional setting, the detection of response conflict, the experience of difficulty, etc.) are incorporated into the episodic file, as well (see also Spapé & Hommel, 2008). For instance, if the previous trial was incongruent and the current trial is incongruent as well, the whole previous episode will be reactivated, including the detection of response conflict and the attentional setting (i.e., focusing on the relevant stimulus dimension) to deal with this response conflict. In contrast, if the previous trial was congruent but the current trial is incongruent, the previous and current episode files do not match in terms of the detection of

[3] One reason for these mixed results might be that these studies differed with respect to their motivational aspects (e.g., whether or not they involved performance-contingent rewards). Reward also modulates the Gratton effect (e.g., Braem, Verguts, Roggeman, & Notebaert, 2012), and motivational and affective influences on the Gratton effect can be dissociated (Dreisbach & Fischer, 2012b; see also Braem et al., 2013).

response conflict and attentional setting, leading to impaired processing of the current trial (Egner, 2014; Spapé & Hommel, 2008). The idea that associations are formed between cognitive control states (e.g., task-demand units) and the currently relevant trial features (e.g., the current stimulus), and that these associations are strengthened when control state and trial features occur together, can also be found in several computational models of cognitive control (e.g., Botvinick et al., 2001; Verguts & Notebaert, 2008; see also Blais, Robidoux, Risko, & Besner, 2007; Brown et al., 2007; Jiang, Heller, & Egner, 2014).

This associative-learning perspective might be further extended to explain conflict-control loops in multitasking as they are proposed in the present article. For instance, the detection of task conflict might constitute another feature of the internal cognitive state that is also integrated into the episode file. Also, the negative affective component of experienced conflict, and its associated avoidance motivation, might constitute features that are integrated into the episodic file. Further (computational) work will be necessary to evaluate the explanatory power of this perspective.

In general, the associative-learning perspective of cognitive control, as proposed by Abrahamse et al. (2016) and Egner (2014), seems appealing, in that several empirical phenomena that are usually taken as empirical signatures of cognitive control (e.g., the Gratton effect) can be explained by associative learning and binding mechanisms. However, we note that this perspective still assumes that cognitive control is in place. For instance, control processes such as detecting conflict or establishing an attentional setting are assumed to be features of the current state of the cognitive system. The associative-learning perspective does not explain how exactly these control processes work. In our opinion, it remains to be established whether the associative-learning view really provides more parsimonious explanations of cognitive control mechanisms.

Conclusion

To conclude, the perspective of conflict-control loops in multitasking assumes that conflict monitoring and control adjustments occur at different levels in the cognitive system, with affective and associative-learning mechanisms potentially playing an important role in these conflict-control loops. This perspective proves useful for integrating existing research from both single-task and multitasking paradigms. We expect that this perspective will stimulate future research, advancing our knowledge of the cognitive control processes involved in human multitasking.

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