On the distinction of different types of between-task interference in dual-tasks

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Contents

I Abstract

The widely-accepted response selection bottleneck model of dual-tasking assumes that two tasks gain access to the stage of central processing in a strictly serial manner. However, a frequent observation that contradicts this assumption is that performance in Task 1 is already influenced by certain aspects of Task 2. Such observations were thus termed *backward crosstalk effects* (BCEs). For instance, response times (RTs) in Task 1 are shorter when the required Response 1 and Response 2 overlap spatially (the R1-R2 BCE) and when Stimulus 1 and Response 2 overlap conceptually (the S1-R2 BCE) than when they do not – the compatibility-based BCEs. Similarly, RTs in Task 1 are shorter when a Response 2 is given (go-trial) than when it is withheld (no-go trial) – the no-go BCE. The main question of the present dissertation was: Can we distinguish different types of backward crosstalk? To answer this question the no-go BCE was compared to the compatibility-based BCEs based on its underlying processing stages (Study 1), the mechanism it is caused by (Study 2), and the way in which task processing is adjusted following a no-go trial (Study 3). The results of Studies 1-3 indicate that the no-go BCE results from temporal overlap of Task 1 motor execution with Task 2 central stage, that it is caused by the inhibition of a prepared Response 2, and that the preparation state for Task 2 is adjusted following a no-go trial. As the no-go BCE differs fundamentally from the compatibility-based BCEs in the three aspects investigated here, both should be seen as two different types of BCEs. Furthermore, the R1-R2 BCE and the S1-R2 BCE were compared based on their underlying processes (Study 4). Results of Study 4 suggest that even though both phenomena arise in Task 1 central stage, they are based on different processes, and hence should be seen as two different types of compatibility-based BCEs. To answer the present main question: Different types of backward crosstalk can indeed be distinguished. As each type of backward crosstalk contradicts the notion of an encapsulated central stage in a different way, the present results support capacity-sharing over strictly serial processing.

II Zusammenfassung

Das zentrale Flaschenhalsmodell nimmt an, dass in Doppelaufgaben beide Aufgaben seriell Zugang zur zentralen Verarbeitungsstufe erhalten. Befunde, dass die Performanz in Aufgabe 1 von bestimmten Aspekten der Aufgabe 2 beeinflusst wird – sogenannte *backward crosstalk Effekte* (BCEs) – widersprechen dieser Annahme jedoch. Beispiele für (kompatibilitätsbezogene) BCEs sind die Beobachtungen, dass Reaktionszeiten (RTs) in Aufgabe 1 kürzer sind, wenn Reaktion 1 und Reaktion 2 räumlich überlappen (der R1-R2 BCE) und wenn Stimulus 1 und Reaktion 2 konzeptuell überlappen (der S1-R2 BCE), als wenn dies nicht der Fall ist. Ein weiteres Beispiel ist der no-go BCE, also die Beobachtung, dass RTs in Aufgabe 1 kürzer sind wenn Aufgabe 2 eine Reaktion fordert (go Durchgang), als wenn dies nicht der Fall ist (no-go Durchgang). Die Hauptfrage dieser Dissertation war: Können verschiedene Typen von backward crosstalk unterschieden werden? Um diese Frage zu beantworten wurde der no-go BCE mit den kompatibilitätsbezogenen BCEs bezüglich der beteiligten Verarbeitungsstufen (Studie 1), dem Mechanismus durch den er verursacht wird (Studie 2) und anhand der Verarbeitungsanpassung nach einem no-go Durchgang (Studie 3) verglichen. Die Ergebnisse der Studien 1-3 deuten darauf hin, dass der no-go BCE durch zeitliche Überlappung der motorischen Ausführung in Aufgabe 1 und der zentralen Stufe in Aufgabe 2 ermöglicht, durch die Inhibition einer vorbereiteten Reaktion 2 verursacht und, dass der Vorbereitungsstatus für Aufgabe 2 nach einem no-go Durchgang angepasst wird. Da sich der no-go BCE in den drei hier untersuchten Aspekten fundamental vom kompatibilitätsbezogenen BCE unterscheidet, sollten beide Phänomene als zwei unterschiedliche Typen der BCEs angesehen werden. Außerdem wurden der R1-R2 BCE und der S1-R2 BCE anhand ihrer zugrundeliegenden Prozesse verglichen (Studie 4). Die Ergebnisse von Studie 4 legen nahe, dass beide Phänomene auf unterschiedlichen Prozessen beruhen, obwohl beide in der zentralen Stufe entstehen. Daher sollten beide Phänomene als

unterschiedliche Typen kompatibilitätsbezogener BCEs gesehen werden. Um die gegenwärtige Hauptfrage zu beantworten: Verschiedene Typen von backward crosstalk können unterschieden werden. Da jeder dieser Typen der Annahme einer eingekapselten zentralen Stufe auf unterschiedliche Weise widerspricht, unterstützen die vorliegenden Ergebnisse Kapazitätsverteilungsansätze gegenüber strikt serieller Verarbeitung.

III Publications

III.I Enclosed publications and author contributions

Study 1

Durst, M., & Janczyk, M. (2018). The motor locus of no-go backward crosstalk. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 44,* 1931–1946.

Author	**Author position**	**Scientific ideas %**	**Data generation %**	**Analysis & interpretation %**	**Paper writing %**
Durst, M.	1	25%	75%	70%	75%
Janczyk, M.	2	75%	25%	30%	25%
Titel of paper:		The motor locus of no-go backward crosstalk.			
Status in publication process:		Published			

Study 2

Durst, M., Ulrich, R., & Janczyk, M. (2019). To prepare or not to prepare? When preparation of a response in Task 2 induces extra performance costs in Task 1. *Psychonomic Bulletin & Review*. Advance online publication. https://doi.org/10.3758/s13423-019-01581-1

Author	**Author position**	**Scientific ideas %**	**Data generation %**	**Analysis & interpretation %**	**Paper writing %**
Durst, M.	1	40%	75%	45%	65%
Ulrich, R.	2	20%	0%	20%	10%
Janczyk, M.	3	40%	25%	35%	25%
Titel of paper:		To prepare or not to prepare? When preparation of a response in Task 2 induces extra performance costs in Task 1.			
Status in publication process:		Published			

Study 3

Durst, M., & Janczyk, M. (2019). Two types of backward crosstalk: Sequential modulations and evidence from the diffusion model. *Acta Psychologica, 193,* 132–152.

Author	**Author position**	**Scientific ideas %**	**Data generation %**	**Analysis & interpretation %**	**Paper writing %**
Durst, M.	1	40%	75%	65%	75%
Janczyk, M.	2	60%	25%	35%	25%
Titel of paper:		Two types of backward crosstalk: Sequential modulations and evidence from the diffusion model.			
Status in publication process:		Published			

Study 4

Durst, M., Bratzke, D., Ulrich, R., Janczyk, M. (revision invited). Two different types of compatibility-based backward crosstalk in dual-tasks. *Journal of Experimental Psychology*. *Human Perception and Performance*.

Author	**Author position**	**Scientific ideas %**	**Data generation %**	**Analysis & interpretation %**	**Paper writing %**
Durst, M.	1	30%	75%	40%	40%
Bratzke, D.	2	15%	0%	25%	25%
Ulrich, R.	3	15%	0%	5%	10%
Janczyk, M.	4	40%	25%	30%	25%
Titel of paper:		Two different types of compatibility-based backward crosstalk in dual-tasks.			
Status in publication process:		Revision invited			

III.II Further publications

Janczyk, M., Renas, S., & Durst, M. (2018). Identifying the locus of compatibility-based backward crosstalk: Evidence from an extended PRP paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 44,* 261-276.

Renas, S., Durst, M., & Janczyk, M. (2018). Action effect features, but not anatomical features, determine the backward crosstalk effect: Evidence from crossed-hands experiments. *Psychological Research, 82,* 1-11.

III.III Conference contributions and invited talks

Durst, M., & Janczyk, M. (2016). *Der Entstehungsort von Backward Crosstalk in Doppelaufgaben*. Talk given at A-Dok Doktoranden-Workshop der Allgemeinen Psychologie, Freiburg, Germany.

Durst, M. (2016). *Dual-task costs and between task interference*. Talk given at the University of Nevada, Reno, NV.

Durst, M., & Janczyk, M. (2017). *Identifying the locus of compatibility-based backward crosstalk: Evidence from an extended PRP paradigm*. Talk given at Tagung experimentell arbeitender Psychologen, Dresden, Germany.

Durst, M., & Janczyk, M. (2017). *Identifying the locus of no-go based backward crosstalk: Evidence from an extended PRP paradigm*. Talk given at A-Dok Doktoranden-Workshop der Allgemeinen Psychologie, Ulm, Germany.

Durst, M., & Janczyk, M. (2017). *Identifying the locus of no-go based backward crosstalk: Evidence from an extended PRP paradigm*. Talk given at the European Society for Cognitive Psychology, Potsdam, Germany.

Durst, M., & Janczyk, M. (2018). *Sequential modulation of compatibility-based and no-go-based backward crosstalk – insights from diffusion model analyses*. Talk given at Tagung experimentell arbeitender Psychologen, Marburg, Germany.

Durst, M., & Janczyk, M. (2018). *Two types of compatibility-based backward crosstalk*. Poster presented at A-Dok Doktoranden-Workshop der Allgemeinen Psychologie, Mainz, Germany.

Durst, M., & Janczyk, M. (2018). *Response preparation determines the direction of no-go backward crosstalk*. Poster presented at the 59th Annual Meeting of the Psychonomic Society, New Orleans, LA

1. Introduction

The dawning of the information age had a massive impact on how humans organize their everyday life. Take, for instance, the emergence of computers and artificial intelligence, which automatized formerly time-costly tasks and left us with more time for other important duties. Nowadays, much time can be saved by, for instance, sending documents via E-mail instead of having to pack them, take them to the post office, and wait for them to arrive at the target address. However, this new world of digitalization and remoteness may come at costs that are yet to fathom. It is expected that the rapid progress of information technology will change our everyday and work life forever. Besides the socio-economic consequences, evidence from applied psychological fields suggests that the increased degree of automaticity can even affect human behavior by fostering situations that allow for multitasking.

For instance, the emergence of cell phones enabled humans to communicate while doing something else. While this may appear as a facilitation of our everyday life, it can also be dangerous. Results from applied psychological studies indicate that having a conversation on the cell phone while driving decreases driving performance (Strayer & Drews, 2004, 2007) and that this was even the case when participants had to manually respond to simple stimuli (Levy & Pashler, 2008) across a wide range of stimulus- and response-modalities (Hibberd, Jameson, Carsten, 2013). Similar results were observed in educational contexts. Students who engaged in media use during educational sessions remembered less content (Hembrooke, & Gay, 2003; Wood et al., 2012) and were slower in reading (Bowman, Levine, Waite, & Gendron, 2010). Taken together, results from applied research indicate that in everyday life multitasking can lead to reduced performance and that it can actually increase levels of subjective strain (Paridon & Kaufmann, 2010). But why do performance decrements in multitasking arise?

The reasons for performance decrements in multitasking have been extensively studied in cognitive psychology. Here, what is popularly called multitasking is investigated in dual-task experiments where participants perform two tasks in close temporal succession or simultaneously. In Chapter 2 of the present dissertation, I will introduce how dual-tasking experiments are usually carried out and how dual-task models explain performance decrements. In Chapter 3, I will turn to the phenomenon of backward crosstalk, which in contrary to the assumptions made by a popular model of dual-tasking indicates that humans are to some extent able to process two tasks in parallel. I will argue for the existence of two types of backward crosstalk that differ in the cognitive processing stage in which they arise and in the mechanisms they are caused by. In Chapter 4, I will expand on other phenomena arising in dual-tasking experiments and explain if and why they are comparable to backward crosstalk, before I will lay out the research questions of the present dissertation in Chapter 5. The studies I carried out to answer these questions will be presented in Chapter 6, and the respective answers will be given in Chapter 7.

2. Dual-tasking and models of dual-tasking

In cognitive psychology research, multitasking has been primarily investigated with three setups that differ in the way two tasks are combined. In the single- vs. dual-task setup participants perform blocks comprising only one of the two tasks (single-task blocks), blocks in which both tasks are presented as single-tasks in a randomly intermingled fashion (mixed blocks), and blocks in which both tasks have to be carried out in a single trial (dual-task blocks; e.g., Janczyk, Nolden, & Jolicoeur, 2015; Tombu & Jolicoeur, 2004). In the Psychological Refractory Period (PRP) setup (Pashler, 1994; Welford, 1952), participants perform two tasks in close temporal succession in each trial, whereas in the task switching setup participants perform one of two tasks in each trial but occasionally have to switch between both tasks on a trial-by trial basis (e.g., Rogers & Monsell, 1995; Meiran, 1996). While all three setups are valuable approaches to help identify the cognitive structure and flexibility issues in multitasking, the present dissertation focusses on the PRP paradigm where two tasks are performed concurrently.

In the PRP paradigm, participants first give Response 1 to Stimulus 1 and successively give Response 2 to Stimulus 2. The dependent variable of interest in the PRP paradigm are response times (RTs) to both stimuli, measured from the onset of each stimulus until the according response is given. The crucial manipulation in the PRP paradigm is the temporal delay between the onset of Stimulus 1 and Stimulus 2 – the stimulus onset asynchrony (SOA, see Figure 1a for an illustration). The temporal overlap of Task 2 and Task 1 thus increases with decreasing SOA. Dual-tasking is known to lead to performance decrements in terms of increased RTs for both tasks relative to when they are performed in isolation. Thus, these decrements have often been termed dual-task *costs*. Performance decrements for Task 1, which are indicated by longer Task 1 RTs when Task 1 is performed alone relative to in the presence of Task 2, were reported by several studies applying the PRP paradigm (Karlin & Kestenbaum, 1968; Smith, 1969; for a review, see Herman & Kantowitz, 1970) and by studies applying the prioritized processing paradigm (Miller & Durst, 2014, 2015). [1] Whilst Task 1 is usually unaffected by the amount of temporal overlap between Task 1 and Task 2, Task 2 RTs are longer, the shorter the SOA is – the *PRP effect* (see Figure 1b for an illustration; Pashler, 1994; Telford, 1931) indicating performance decrements for Task 2 (see Janczyk, Pfister, Wallmeier, & Kunde, 2014, for possible exceptions).

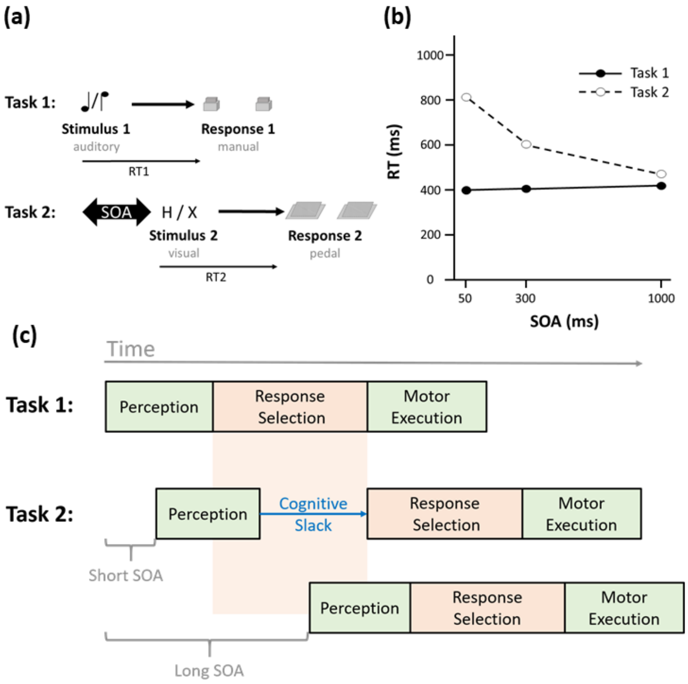

Figure 1. (a) Illustration of the Psychological Refractory Period (PRP) paradigm. In this particular example, Task 1 requires a manual response to an auditory stimulus, whereas Task 2 requires a pedal response to a visual stimulus. While Stimulus 1 is presented immediately at the beginning of each trial, the onset of Task 2 is delayed by the stimulus onset asynchrony (SOA). (b) Illustration of a typical results pattern in a PRP experiment. (c) Illustration of the response selection bottleneck model by Pashler (1994).

The PRP effect is usually explained with the widely-accepted response selection bottleneck model (RSB; Pashler, 1984). The RSB model assumes that each task is processed in three subsequent cognitive stages. First of all, in the perception stage, the according stimulus is

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[1] The prioritized processing paradigm is closely related to the PRP paradigm, and it leads to qualitatively similar results (Miller & Durst, 2015). Here participants are also presented with two tasks in close temporal succession. In contrast to the PRP paradigm, however, participants are instructed to respond to Task 2 only if Task 1 does not require a response.

perceived. Subsequently, the task is processed in the central stage of processing, before the according response is finally carried out in the motor execution stage. The perception and motor execution stages are assumed to be capacity unlimited, which means that they can run in parallel to all stages of another task. However, the central stage is conceived of as capacity limited, which means that it can only process one task at a time while the other task has to wait until the central stage is available again. It was assumed that the central stage deals with the translation of stimulus codes into the according response codes (e.g., Fagot & Pashler, 1992; McCann & Johnston, 1992), and that it is limited to the translation of one stimulus-response rule at a time. The central stage can thus be conceived of as *structural* bottleneck in human cognition. It follows that, at a short SOA, Task 2 has to wait until the central stage has been released from Task 1. The idle time during which Task 2 waits is called the *cognitive slack*. Task 2 RTs are then accordingly prolonged by the duration of the cognitive slack. At long SOAs, however, Task 2 can get access to the central stage without waiting time and Task 2 RTs remain unaffected (see Figure 1c for an illustration).

As an alternative to the strictly serial processing as envisaged by the RSB model, capacity sharing accounts suggested that a common cognitive resource is shared between both tasks (Navon & Miller, 2002; Tombu & Jolicoeur, 2003; for a review see Fischer & Plessow, 2015). Thus, in contrast to the RSB model, capacity sharing accounts allow parallel processing by assigning a certain amount of resources to each task. The efficiency at which each task is processed then depends on the amount of resources assigned to the according task, as both tasks only get a share of the available resources. Thus, capacity sharing accounts still allow for serial processing, if one of both tasks is assigned all available resources. Recent evidence indicates that the distribution of capacity between tasks is adjusted in order to increase overall performance (Miller, Ulrich, & Rolke, 2009) and by the prerequisites of the dual-tasking paradigm in use (Mittelstädt & Miller, 2017).

A further, perhaps less known account was proposed by Navon and Miller (1987). According to their crosstalk account, each task "produces outputs, throughputs, or side effects" (Navon & Miller, 1987, p. 435) that can affect processing of the respective other task (see also Pashler, 1994, for a distinction into serial processing, capacity sharing and crosstalk models). The crosstalk model is supported by results of conflict task experiments, where one stimulus (or stimulus feature) requires a particular response, while another task-irrelevant stimulus (or stimulus feature) requires the same or a different response (e.g. the Simon task, Simon & Rudell, 1967; the Eriksen flanker task, Eriksen & Eriksen, 1974; the Stroop task, Stroop, 1935). In these studies usually shorter RTs are observed when both stimuli (or stimulus features) require the same compared to different response. According to Navon and Miller (1987), such crosstalk effects should be even larger when the second stimulus at some point becomes task-relevant. This is, for instance, the case in dual-task studies in which the similarity of stimulus and response codes varies on a trial-by trial basis. Such studies usually observe that performance of Task 1 is influenced by aspects of Task 2 – the so-called *backward crosstalk effects* (BCEs).

While BCEs seem well in line with the crosstalk account, they pose theoretical problems for other dual-task models, because they indicate that to some extent response related output or response codes of Task 2 must have already been available in order to influence performance in Task 1. While at first glance this appears to be in line with capacity sharing accounts, these accounts would still have to be extended to account for BCEs. For instance, the way in which stimulus and response codes are passed on between tasks and how exactly they influence performance of the according task would need to be specified. Even more so, the BCEs challenge the assumption of strictly serial processing as made by the RSB model. In the following chapter, I will explain under which preconditions BCEs arise, how they manifest, and how the RSB model was extended in order to account for BCEs.

3 Backward Crosstalk

A large body of studies observed influences of *several* aspects of Task 2 on RTs of Task 1. In the following I will introduce the classic experimental paradigms in which each type of BCE was observed, followed by the available theoretical explanations for each type of BCE. I will begin with two types of compatibility-based BCEs – namely the R1-R2 BCE and the S1-R2 BCE – and will then turn to the no-go BCE.

3.1 The compatibility-based BCEs:

A frequent observation in dual-task experiments is that performance in Task 1 depends on the dimensional overlap of Task 1 with Task 2 (for a detailed consideration of dimensional overlap, see Kornblum, Hasbroucq, & Osman, 1990). Usually, RTs in Task 1 are shorter when dimensional overlap between both tasks is given relative to when there is no dimensional overlap – the *compatibility-based BCEs* (see Figure 2 for an idealized illustration of the related result pattern). This was observed in two cases: (1) when dimensional overlap of Response 1 and Response 2 was present (the R1-R2 BCE) and (2) when dimensional overlap of Stimulus 1 and Response 2 was present (the S1-R2 BCE).

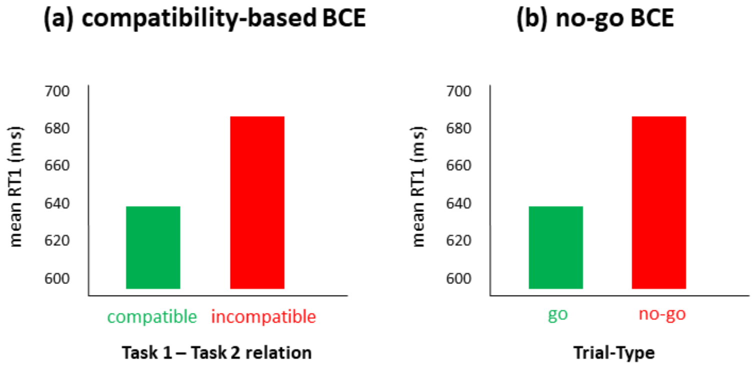

Figure 2. Illustration of the idealized result patterns, as they are expected for (a) the R1-R2 or S1-R2 BCE, and (b) the no-go BCE.

3.1.1 Experimental setups

Compatibility-based BCEs were first reported by Hommel (1998). Hommel investigated whether translations from stimulus to response can occur concurrently. He reasoned that parallel stimulus-response translations in both tasks would be indicated by an influence of dimensional overlap of both tasks on RTs in Task 1. Precisely, when features of both tasks overlap in a common dimension, Hommel expected shorter RTs in Task 1 relative to without dimensional overlap.

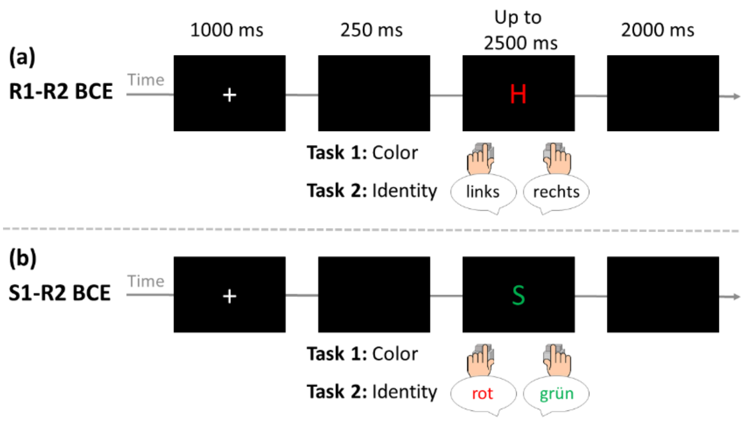

Figure 3. (a) Illustration of the trial structure of Hommel's (1998) Experiment 1. This setup allows for spatial overlap of both responses, and thus the R1-R2 BCE is enabled. (b) Illustration of the trial structure of Hommel's (1998) Experiment 2. This setup allows for a conceptional overlap of Stimulus 1 (the color) and the vocal response, and thus the S1-R2 BCE is enabled.

In Experiment 1, Hommel (1998) presented his participants with the letters 'H' or 'S' colored in red or green in each trial. Participants were instructed to first respond to the color of the letter with a left vs. right index finger keypress in Task 1, and to subsequently respond to the identity of the letter with a vocal 'links' (German for 'left') vs. 'rechts' (German for 'right') utterance in Task 2 (see Figure 3a for an illustration). This enabled spatial overlap of both responses: If Response 1 and Response 2 overlapped, both responses were compatible (e.g., a left index finger keypress and a vocal 'left' response), whereas Response 1 and Response 2 were incompatible if they did not overlap (e.g., a left index finger keypress and a vocal 'right' response).[2] Hommel observed shorter RTs in Task 1 (and also in Task 2) when both responses were spatially compatible relative to when they were incompatible – the R1-R2 BCE.

In Experiment 2, stimuli and responses were the same as in Experiment 1. However, now participants were instructed to respond to the identity of the letter with the vocal utterance 'rot' (German for 'red') vs. 'grün' (German for 'green'). This enabled conceptual overlap between the color of Stimulus 1 and the vocal utterance in Response 2: Stimulus 1 and Response 2 were compatible when the color of Stimulus 1 matched the word uttered in Response 2 (e.g., a letter colored in red and the word 'rot' uttered), whereas Stimulus 1 and Response 2 were incompatible when the color of Stimulus 1 did not match the word uttered in Response 2 (e.g., a letter colored in red and the word 'grün' uttered). Similar to Experiment 1, RTs in Task 1 (and also in Task 2) were shorter when Stimulus 1 and Response 2 were compatible relative to when they were incompatible – the S1-R2 BCE (see Figure 3b).

Compatibility-based BCEs have been reported by a wide range of studies applying different types of dimensional overlaps and response modalities. For instance, the R1-R2 BCE was observed when spatial overlap between two manual responses was enabled (Janczyk, Pfister, Hommel, & Kunde, 2014; Lien & Proctor, 2000; Miller & Durst, 2014, 2015; Thomson, Watter, & Finkelshtein, 2010; Watter & Logan, 2006) or between manual and pedal responses (Janczyk, 2016; Durst & Janczyk, 2019; Renas, Durst, & Janczyk, 2018). The S1-R2 BCE was observed when conceptional overlap was enabled between the color of a stimulus and a vocal

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[2] Note that I labeled the dimensional overlap between both tasks as spatial in line with previous studies (e.g. Janczyk, Renas, & Durst, 2018). However, it could be argued that the vocal "left" or "right" response in this case is not spatial per se, as the participants did not turn their head to respond in the corresponding direction while uttering the response. Watter and Logan (2006) suggested that the need to utter such responses could involve "more abstract conceptual representation of *left* and *right*" (p. 256, emphasized as in the original). If these conceptual representations of left and right are activated (e.g., by perceiving the identity of the letter), they would dimensionally overlap with the semantic information associated with a left vs. right Response 1. The dimensional overlap would in this case be of semantic nature. Note, however, that the true nature of the dimensional overlap in this case is unknown, as the semantic dimension of Response 2 could also overlap with the spatial dimension associated with Response 1.

response (Ellenbogen & Meiran, 2008; Hommel & Eglau, 2002) and auditorily presented spatial stimuli and manual responses (Lien, Ruthruff, Hsieh, & Yu, 2007).

3.1.2 Theoretical explanation

These observations indicate that Response 2 must have been "at least activated to some degree at the time the primary response was selected" (Hommel, 1998, p. 1373). Hommel argued that parallel stimulus-response translation could only be reconciled with the RSB model, if the central stage would be split into two substages of response activation and response selection. He suggested that an automatic and capacity unlimited response activation stage occurs right after the stimulus was perceived. The response activation stage is responsible for increasing the activation level of the according response to a certain degree. In the following response selection stage the activation level of the response is driven above its selection threshold and the response can then be executed in the motor stage (see Figure 4a; see also, Lien & Proctor, 2002). Thus, response selection "may well rely on translation, but this does not mean that all translation processes subserve selection" (Hommel, 1998, p. 1381). The model suggested by Hommel (1998) assumes that only at a sufficiently short SOA response activation stages of both tasks overlap, and only then backward crosstalk occurs.

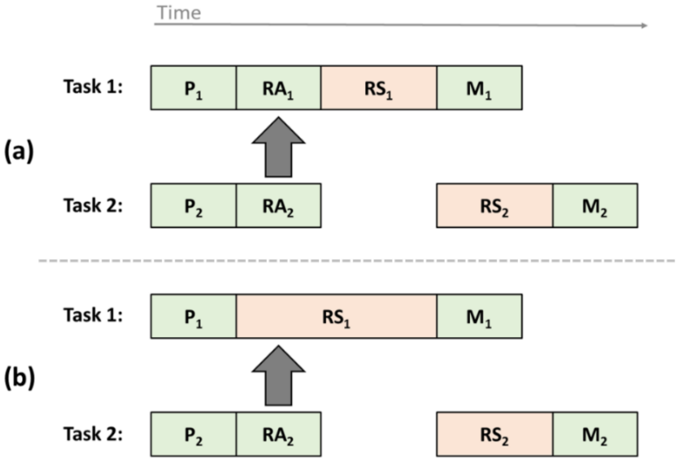

Figure 4. (a) Illustration of the modified RSB model as suggested by Hommel (1998; see also Lien and Proctor, 2002). (b) Illustration of the modified RSB model as suggested by Thomson et al. (2015; see also Janczyk, Renas et al., 2018). (P = perceptual stage; RA = response activation; RS = response selection; M = motor stage)

One possible way in which this model can explain the prolonged Task 1 RTs is that the Task 1 stage in which backward crosstalk occurs, is prolonged in incompatible relative to compatible trials. The prolongation of a certain Task 1 stage accordingly delays the onset of the following processing stages, and thus prolongs Task 1 RTs in incompatible relative to compatible trials. In the following, I will thus conceive of the Task 1 stage in which the BCE arises as the *locus* of the BCE.

As an alternative to the model suggested by Hommel (1998), Thomson, Danis, and Watter (2015) suggested that Task 1 response selection starts directly after stimulus identification. In Task 2, however, response activation only occurs if Task 2 does not gain direct access to the bottleneck (see Figure 4b for an illustration). Thomson et al. trained their participants in a dual-task, which is assumed to shorten the response selection stage in both tasks (Strobach, Liepelt, Pashler, Frensch, & Schubert, 2013). If the locus of the BCE is in Task 1 response selection, the authors expected that a shortened Task 1 response selection stage should lead to a decreased BCE due to less temporal overlap with Task 2 response activation. In line with this assumption, Thomson et al. observed that the BCE decreased with training. They concluded that response information, generated automatically in Task 2 response activation, feeds into Task 1 response selection and is added to this controlled process.

In order to distinguish between the models suggested by Hommel (1998) and Lien and Proctor (2002) and the model suggested by Thomson et al. (2015), Janczyk, Renas et al. (2018) recently investigated the locus of the compatibility-based BCEs by applying the locus of slack (Schweickert, 1978) and the effect propagation logic to an extended PRP paradigm. Note that their logic hinges on the assumption that response activation and response selection are sequential processing stages, which is well accepted in the literature (see Janczyk, Renas et al., 2018, for details; see also, e.g., Paelecke & Kunde, 2007; Schubert et al., 2008). In Experiment 1, Janczyk, Renas et al. applied the locus of slack logic to investigate whether the R1-R2 BCE arises (a) in a stage before or (b) during or after the bottleneck. Because evoking compatibility-based BCEs already requires two tasks, a third task had to be added to enable the locus of slack logic: Task 1 occupied the bottleneck, Task 2 was the task in which the BCE was observed, and Task 3 was the task causing the BCE in Task 2. Each trial started with the presentation of a low or high tone requiring a vocal "tip" vs. "top" response (Task 1). After a variable SOA, a red or green "H" or "S" was presented as integral stimulus. The color required an index-finger keypress of the left vs. right hand (Task 2), whilst the letter identity required a pedal press of the left vs. right foot (Task 3).

First, consider the assumption that the BCE arises in a prebottleneck stage, such as the response activation stage. At a sufficiently short SOA, the amount by which Task 2 response activation is prolonged in incompatible trials reaches inside the cognitive slack and does not exceed it – it is *absorbed* into slack. Thus, the following stages are not further postponed by any prolongation of response activation. Consequently, Task 2 RTs are not prolonged (see Figure 5a) in incompatible trials. In this case an underadditive interaction of SOA and the BCE is predicted. At a sufficiently long SOA, however, the BCE should be observed, as the prolonged Task 2 response activation stage in incompatible trials in turn also postpones the

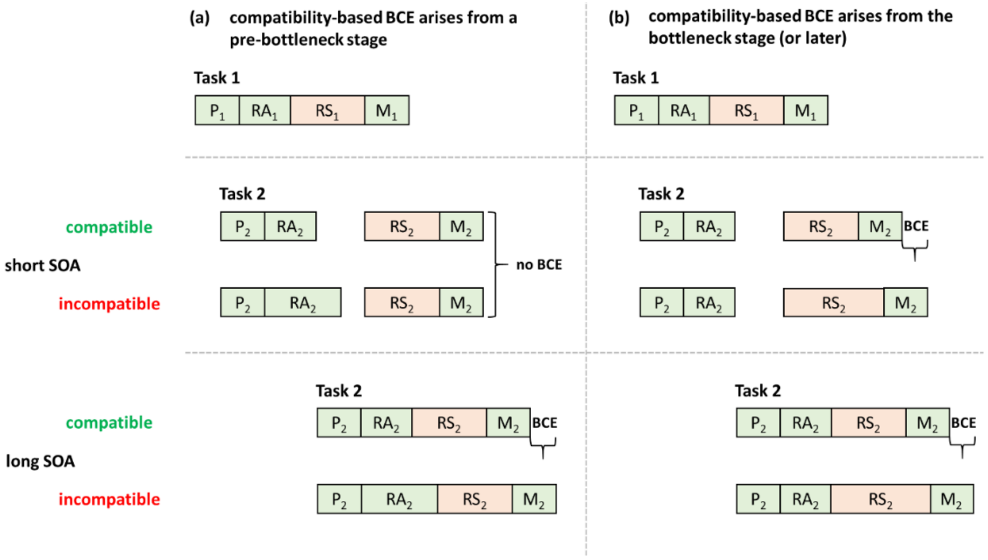

Figure 5. Illustration of the locus of slack logic applied to an extended PRP paradigm. Panel (a) illustrates the case when the compatibility-based BCE arises from a prolonged response activation. Panel (b) illustrates the case when the compatibility-based BCE arises from a prolonged response selection stage (the predictions for a prolonged motor execution stage are the same). Task 3 was omitted in this illustration. (P = perceptual stage; RA = response activation; RS = response selection; M = motor stage)

subsequent stages. This accordingly leads to longer RTs in Task 2 (see Figure 5a). Under the assumption that the BCE arises during the bottleneck or later, it is predicted that a prolongation in the response selection or motor execution stage leads to the same RTs. Thus, the BCE is expected to be of the same size at the short and long SOA (see Figure 5b), and accordingly an additive pattern of Task 2 RTs is expected.

Janczyk, Renas et al. (2018) indeed obtained no significant interaction of SOA and BCE for the R1-R2 BCE in Experiment 1 and for the S1-R2 BCE in Experiment 3. They also replicated this result for the R1-R2 BCE in their Experiment 2 where only two responses were required in each trial (in Task 1 and in Task 2 or Task 3), which supports the assumption that S2-R2 translation is automatic for compatibility-based BCEs (see Hommel, 1998, Experiment 5). Janczyk, Renas et al. concluded that compatibility-based BCEs arise in a stage during or after the bottleneck. To further distinguish between response selection and motor execution, the effect propagation logic was used in Experiment 4.

To this end, the same tasks were used but in reversed order. In Experiment 4, Task 1 was the task in which the BCE was observed (manual response to the color of the letter), Task 2 was the task causing the BCE (pedal response to the identity of the letter), and Task 3 was the non-related task (vocal response to the frequency of a tone) which was presented after a variable SOA. First consider the assumption that the BCE has its locus in or before the bottleneck. At a sufficiently short SOA, the amount by which any central or precentral stage in Task 1 is prolonged, accordingly delays the onset of the response selection and motor execution stages of Task 2 and Task 3 by the same amount of time. It follows that the BCE observed in Task 1 is also observed in Task 2 and Task 3, and thus fully propagates to Task 3 (see Figure 6a). At a sufficiently long SOA, however, the BCE should not propagate to Task 3, as the onset of Task 3 response selection is not delayed. Under the assumption of a locus after the central stage, any prolongation of the motor stage of Task 1 should not delay the onset of response selection of Task 2 and Task 3, and thus no propagation to Task 3 should be observed (see Figure 6b).

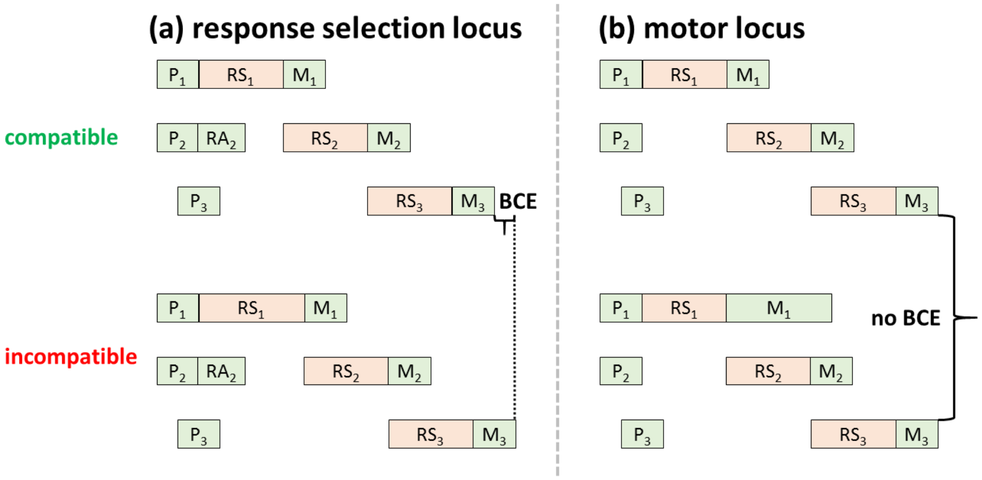

Figure 6. Illustration of the effect propagation logic applied to an extended PRP paradigm. Panel (a) illustrates the case of the full propagation of the compatibility-based BCE. Panel (b) illustrates the case when the compatibility-based BCE does not propagate to Task 3. The long SOA was omitted here. (P = perceptual stage; RA = response activation; RS = response selection; M = motor stage; the subscript indicates Task 1, Task 2, and Task 3, respectively)

Janczyk, Renas et al. (2018) observed that the BCE indeed fully propagated to Task 3 and concluded that the compatibility-based BCEs have their locus in a stage at or prior to the bottleneck (for further evidence from a different paradigm, see Experiment 5 of Janczyk, Renas et al., 2018). Taken together, a locus prior to the bottleneck was ruled out applying the locus of slack logic, and a locus after the bottleneck was ruled out applying the effect propagation logic. Thus, compatibility-based BCEs have their locus inside the central stage, which contradicts the assumption that the compatibility-based BCEs are located in a capacity-unlimited response activation stage that precedes the central stage.

As the compatibility-based BCEs have their locus in the capacity-limited stage of processing (which is the response selection stage according to Pashler, 1994), Janczyk, Renas et al. (2018) concluded that the assumption of a response activation stage preceding the central stage in Task 1 is not needed (see also Thomson et al., 2015). However, automatic stimulus to response translation still seems to occur in Task 2. Janczyk, Renas et al. thus suggested that a response activation stage in Task 2 occurs, if Task 2 has to wait to gain access to the bottleneck.

Then, Stimulus 2 activates the according response to some degree without leading to the emission of the response, similar to what is known from conflict tasks such as the Eriksen flanker task (Eriksen & Eriksen, 1974; Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988). The automatic activation for Response 2 is then added to the controlled Task 1 processing, yielding a net activation. Similar mechanisms have, for instance, been suggested by computational models, such as the theory of visual attention (ECTVA; Logan & Gordon, 2001) and the diffusion model for conflict tasks (DMC; Ulrich, Schröter, Leuthold, Birngruber, 2015). As Task 2 response activation causes the BCE, response activation will in the following be conceived of as the *source* of the compatibility-based BCEs.

In a nutshell, Janczyk, Renas et al. (2018) located both compatibility-based BCEs inside the central stage and thus argued in favor of the model suggested by Thomson et al. (2015). Up to this point, it seems as if both compatibility based BCEs share a common locus and source, even though they arise under different preconditions. Whether both compatibility-based BCEs are indeed based on the same processes will be closer investigated in Study 4 of the present dissertation.

3.2 The no-go BCE:

So far, compatibility-based BCEs have received the most attention in the literature. However, BCEs can even be observed without dimensional overlap. One example is the observation that RTs in Task 1 are shorter when Task 2 requires a response relative to when it does not require a response – the *no-go BCE* (see Figure 2b for an idealized illustration of the related result pattern).

3.2.1 Experimental setup

Miller (2006) investigated whether the phenomenon of backward crosstalk is restricted to certain very specific combinations of tasks in between which dimensional overlap is given, or whether it is a rather general phenomenon. To this end, Miller avoided overlap in stimuli, stimulus-response rules or responses in both tasks. In Experiment 1 and 2 a manual two-choice Task 1 was combined with a manual go/no-go Task 2 (see Donders, 1969). While participants responded with the index or middle finger of the left hand in Task 1, they were instructed to either respond with a keypress of their right index finger or to withhold this response in Task 2. Miller reasoned that the inhibition needed to withhold the response in a no-go Task 2 could spill over to Task 1. If this were the case, Task 1 RTs should be prolonged when Task 2 is a no-go relative to go task. The observation of a no-go BCE would indicate that backward crosstalk is a rather general than a specific phenomenon.

In Experiment 1, Miller (2006) presented the letters 'X' and 'O' which were followed by a high vs. low tone after a variable SOA (of 100, 200, or 400 ms). Participants were instructed to first respond to the identity of the letter with a middle vs. index finger keypress of the left hand in Task 1, and to subsequently respond to the frequency of the tone with an index finger keypress of the right hand or by withholding the response in Task 2. Trials in which a response was given in Task 2 were considered go-trials, whereas trials in which the response in Task 2 was withheld were considered no-go trials (see Figure 7). Task 1 RTs were shorter in go relative to no-go trials. However, the no-go BCE did not decrease with increasing SOA. This observation can be taken as evidence that compatibility-based BCEs and the no-go BCE are based on different processes. I will elaborate on this issue in Study 1 of the present dissertation.

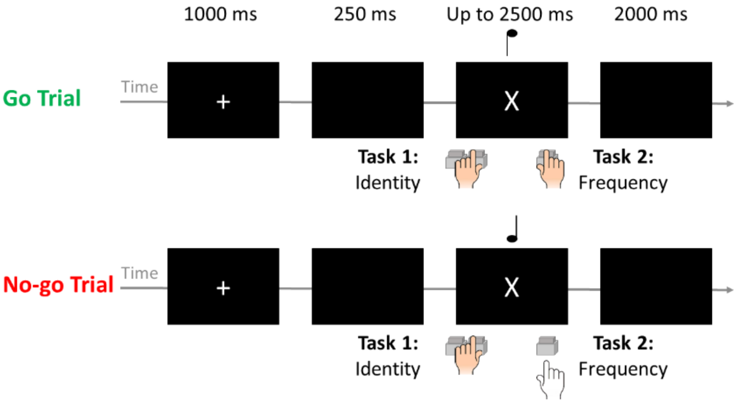

Figure 7. Illustration of the trial structure of a no-go BCE experiment similar to Miller (2006).

The no-go BCE was replicated in several more recent studies. For instance, with a pedal go/no-go Task 2 (Ko & Miller, 2014), and in the prioritized processing paradigm (Miller & Durst, 2014, 2015). However, the processes underlying the no-go BCE as well as its locus and source are still debated.

3.2.2 Theoretical explanation

The inhibition hypothesis is based on the assumption that withholding a response in a no-go trial involves active inhibition of this response (see Brunia, 1983; Heil, Osman, Wiegelmann, Rolke, & Hennighausen, 2000; Sasaki, Gemba, Nambu, & Matsuzaki, 1993). Miller (2006) suggested that the already prepared response in Task 2 of no-go trials thus also has to be actively inhibited (see also Miller & Durst, 2014, 2015). [3] According to the inhibition hypothesis, the amount of inhibition needed to inhibit an already prepared response depends on the degree to which the response has already been prepared. It follows that, in the case of a well prepared response, more inhibition is needed to withhold it. This assumption was recently supported by Janczyk and Huestegge (2017), who only observed the no-go BCE when Task 2 was a simple go/no-go task, and thus very easy to prepare. The inhibition needed to withhold the response in Task 2 then spreads to Task 1 where it prolongs motor execution (Ko & Miller, 2014) and accordingly Task 1 RTs. Miller (2006) suggested that the no-go BCE could result from a “rather general crosstalk between response selection and/or execution processes of the two tasks” (Miller, 2006, p. 492). Thus, from an inhibition hypothesis view, it is reasonable to assume

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[3] The inhibition needed to withhold an already prepared response in a no-go trial has often been equated with the inhibition required to stop responding in stop trials of the stop-signal paradigm (Friedman & Miyake, 2004). Even though it was suggested that inhibition in both paradigms arises in the same processing stage (Bissett, Nee, & Jonides, 2009), other evidence suggests that inhibition in the go/no-go paradigm arises automatically, whereas it arises in a controlled manner in the stop-signal paradigm (Verbruggen & Logan, 2008). As the evidence for the equity of inhibition in both paradigms is mixed, I do not wish to intermingle both paradigms in the present dissertation.

Task 1 motor execution as the locus and Task 2 central stage as the source of the no-go BCE (see Figure 8).

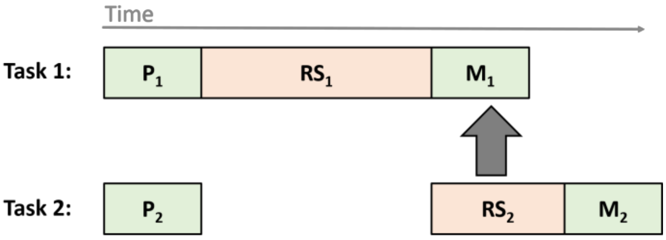

Figure 8. Illustration of a modified RSB model where no-go backward crosstalk arises from the temporally overlapping stages of Task 2 response selection and Task 1 motor execution (Janczyk & Huestegge, 2017; Miller, 2006, see General Discussion for a tentative suggestion). (P = perceptual stage; RS = response selection; M = motor stage)

As an alternative Rötter and Haider (2017) suggested that the no-go BCE arises through automatic response feature activation, similar to what was suggested for the compatibility-based BCEs. The automatic activation hypothesis is based on the assumption that over the course of an experiment, constant stimulus-response parings establish associations of the according stimulus with rather abstract goal representations of giving and withholding responses. Such abstract goal representations could, for instance, be the sensory consequences of not pressing a key (see Kühn, Elsner, Prinz, & Brass, 2009). Henceforth, the no-go stimulus can automatically activate the abstract representations of withholding the response (Verbruggen & Logan, 2008). It follows that, in a no-go trial, the abstract representations of withholding the Task 2 response (e.g., the sensory consequences of not responding) are incompatible with the abstract representations of giving the Task 1 response (e.g., the sensory consequences of responding) and thus prolong RT1s similar to what has been observed for the compatibility-based BCEs. Röttger and Haider tested the response activation hypothesis by comparing the no-go BCE resulting in blocks identical to Miller's (2006) Experiment 1 (forced-choice condition) with blocks in which participants were free to give or withhold their response in Task 2 (free-choice condition). They only observed the no-go BCE when participants were forced not to respond. Röttger and Haider concluded that the no-go BCE is not caused by inhibition, but rather by automatic response feature activation, because the association of an abstract goal representations with a stimulus cannot be established in free-choice blocks where no constant stimulus-response pairings exist. Taken together, Röttger and Haider assumed that the perception of a no-go stimulus in Task 2 automatically impairs performance of Task 1 because of the incompatibility with the sensory consequence of a go response or because of an incompatibility of abstract "go- and no-go representations" via overlapping response activation stages of both tasks. It follows that the no-go BCE arises in the response activation stage of Task 1 or in the central stage (against the background of the Janczyk, Renas et al., 2018; Thomson et al., 2015, studies).

In summary, two hypotheses suggest different models for the no-go BCE. The inhibition hypothesis assumes that the inhibition needed to withhold an already prepared response in Task 2 central stage (the source) also affects Task 1 motor execution (the locus). The automatic activation hypothesis, on the other hand, assumes that the automatic activation of incompatible response features in Task 2 response activation (the source) feeds into the controlled central stage of Task 1 (the locus).

4 Comparable phenomena

Besides the compatibility-based and the no-go BCE, influences of several other aspects of Task 2 on RTs and motor execution of Task 1 have been reported. In the following, I will briefly introduce these BCE-like effects and I will get back to them in the General Discussion, where they will be related to the BCEs under investigation here. Insights about the relations between these comparable phenomena and the BCEs can deliver important implications for dual-tasking research in general.

4.1 The category match effect

One phenomenon akin to the compatibility-based BCEs is the observation that RTs in Task 1 are shorter when the Stimulus in Task 2 is from the same relative to different semantic category – the category match effect. This effect was first reported by Logan and Schulkind (2000), who investigated whether parallel memory retrieval between two tasks is possible. If parallel memory retrieval is possible, RTs in both tasks should be shorter if Stimulus 1 and Stimulus 2 are of the same semantic category (e.g., if both are digits), relative to when they are not (e.g., Stimulus 1 is a digit and Stimulus 2 is a letter). In their Experiment 1, participants had to distinguish between a letter and a digit in Task 1 and in Task 2. Logan and Schulkind observed that RTs in both tasks were indeed shorter when both stimuli were from the same semantic category than when they were from different semantic categories. The authors replicated this result for parity vs. magnitude judgments in their Experiments 2, and for words vs. non-words as semantic categories in Experiment 3 and 4. Logan and Schulkind concluded that parallel memory retrieval is possible. However, the category match effect could not be obtained when different types of stimulus categorizations were needed for both tasks (e.g. when Stimulus 1 required a size judgment and Stimulus 2 required a parity judgment; Logan & Schulkind, 2000, Experiment 2 and 3), and thus seems to depend on a common task set applied in both tasks.

More recent studies support the notion that the category match effect depends on a common task set, even though parallel memory retrieval still occurs when both task sets differ (e.g., when Task 1 is a size judgment task and Task 2 is a parity judgment task; Fischer, Miller, & Schubert, 2007; Oriet, Tombu, & Jolicoeur, 2005). The category match effect was replicated by several other studies (e.g., Logan & Gordon, 2001; Fischer & Hommel, 2012; Plessow, Schade, Kirschbaum, & Fischer, 2012), and it was also observed when participants retrieved episodic memory content (Logan & Delheimer, 2001).

4.2 Response congruency in task switching

A BCE-like phenomenon can also be observed in the task switching paradigm, where RTs are shorter for stimuli that were assigned the same relative to different responses for both tasks. For instance, Kiesel, Wendt, and Peters (2007) instructed their participants to respond with a left index finger keypress if the digit stimulus was smaller than 5 and to respond with a right index finger keypress if it was larger than 5 in the magnitude task. In the parity task they instructed half of their participants to respond with a left index finger keypress if the digit stimulus was odd and to respond with a right index finger keypress if it was even (and vice versa for the other half of participants). Kiesel et al. (2007) observed shorter RTs for stimuli that were assigned the same responses (congruent stimuli) relative to different responses (incongruent stimulus) in both tasks (see also Meiran, 1996; Rogers & Monsell, 1995). Such a response congruency effect appears to be based on the spatial overlap of the responses afforded by the stimulus, and it was even suggested that the response congruency effect “presumably reflects response-activation according to the irrelevant task’s S-R rules” (Kiesel et al., 2007, p. 118). Thus, the response congruency effect in task switching is structurally similar to the compatibility-based BCEs.

4.3 Motor related crosstalk phenomena

Miller (2006, Experiment 3) investigated the influence of increased motor complexity by comparing a single index finger-keypress as response with three index finger-keypresses as response in Task 2 (cf. Hackley & Miller, 1995; Henry & Rogers, 1960; Stief, Leuthold, Miller, Sommer, & Ulrich, 1998). He observed longer Task 1 RTs when Task 2 required three-keypresses relative to a single-keypress and concluded that response complexity in Task 2 “has an at least partially global effect on motor processes” (p. 491).

Another example for the influence of motor aspects of Task 2 on motor execution of Task 1 was reported by Miller and Alderton (2006). In Experiment 1, participants had to respond to the color of a letter with a left index or middle finger keypress in Task 1 and subsequently to the identity of the letter in Task 2 with a soft vs. hard keypress of the right index finger. These authors observed harder keypresses in Task 1 when the response required in Task 2 was a hard relative to soft keypress. This result was replicated with two separate stimulus objects separated by a variable SOA in Experiment 2, where the BCE-like effect of Response 2 force on Response 1 force was *not* modulated by SOA. In Experiment 3, Miller and Alderton applied a flanker paradigm, in which only one of both possible responses had to be carried out, while the other served as a distractor in each trial. Thus, the Task 2 central stage was eliminated in trials where Task 2 was task irrelevant. As the BCE-like effect was no longer observed, the authors concluded that it has its source in Task 2 central stage and its locus in Task 1 motor execution. Note that Miller and Alderton (2006) excluded a motor source, as peak force in Task 1 was usually reached before the onset of Response 2 force (for more arguments see; Miller & Alderton, 2006, General Discussion).

In order to closer investigate the locus and source of such BCE-like motor crosstalk, Ruiz Fernández and Ulrich (2010) used a continuous lever movement in Task 2. In Task 1 participants responded with the left index or middle finger, while in Task 2 participants responded with a short or long ballistic lever movement. In Experiment 1, they observed longer Task 1 RTs when the lever movement was short relative to long – the opposite of what they expected. As the inverted BCE-like effect could have been caused by a force coupling of Response 2 with Response 1, the authors also measured movement times in Task 1 of Experiment 2, where they replicated the BCE-like effect. However, it was also observed that participants pressed the response key for Task 1 longer when the Task 2 lever movement was long relative to short. Ruiz Fernández and Ulrich concluded that the BCE-like effect they observed in both experiments was indeed caused by a force coupling of Response 2 and Response 1 after both responses were selected. Thus, for now, this phenomenon should be treated as unrelated to backward crosstalk.

4.4 Miscellaneous phenomena

There are even more examples of BCE-like phenomena that have not attracted much attention in the literature yet. Examples for such phenomena are, for instance, a BCE-like effect based on overlap of the emotional valence of stimuli (Eder, Pfister, Dignath, & Hommel, 2016; Allen, Lien, & Jardin, 2017) and cross-task compatibility (Koch & Prinz, 2002; Grabbe & Allen, 2012).

5 Research questions

Previous research often generically labeled interference effects in dual-tasks as “backward crosstalk”. However, such phenomena occur under a wide range of different preconditions and it is conceivable that different cognitive processes underlie different types of backward crosstalk. This applies particularly to the compatibility-based BCEs and the no-go BCE, which seem to differ fundamentally in their underlying cognitive processes and in the way they manifest in performance and neurophysiological activity. The compatibility-based BCE has its locus in Task 1 central stage, its source in Task 2 response activation, and it is caused by automatic response feature activation spilling over from Task 2 to Task 1 (for behavioral evidence see, Janczyk, Renas et al., 2018; Thomson et al., 2015; for evidence from the LRP, see Lien, Ruthruff, Hsieh, & Yu, 2007; Miller, 2017). For the no-go BCE, the majority of studies suggested Task 1 motor execution and Task 2 central stage as locus and source, respectively (Miller, 2006; Ko & Miller, 2014), and that the no-go BCE is caused by the inhibition of a prepared Response 2 which spills over to Task 1 (Janczyk & Huestegge, 2017; Miller, 2006; Miller & Durst, 2014, 2015). However, these hypotheses regarding the no-go BCE have not yet been tested.

Another open question is whether the compatibility-based BCEs are actually based on the same cognitive processes. Available evidence for the R1-R2 BCE is in line with the notion that S1-R1 translation is affected by automatic S2-R2 translation. However, it is hard to imagine that the same process underlies the S1-R2 BCE when there is no dimensional overlap in the response codes activated by both stimuli (e.g., when S1 translates into a manual left index finger vs. right index finger response, whereas S2 translates into a verbal “red” vs. “green” response). On the other hand, both compatibility-based BCEs appear to share the same locus and source (see Janczyk, Renas et al., 2018) and both are based on similar working memory structures

(Thomson et al., 2010; Ellenbogen & Meiran, 2008) which suggests that both BCEs could indeed be based on the same processes.

The **main question** of the present dissertation was:

Can we distinguish different types of backward crosstalk?

To address this question the following two subordinate research questions were answered in Studies 1-4 (see Figure 9). The primary research question was: Can we distinguish the no-go BCE from the compatibility-based BCEs, based on its underlying cognitive processes (Study 1), the mechanism it is caused by (Study 2), and the way in which characteristics of the previous trial lead to processing adjustments in the present trial (Study 3)? The secondary research question was: Can we distinguish the S1-R2 BCE from the R1-R2 BCE based on their underlying processes (Study 4)?

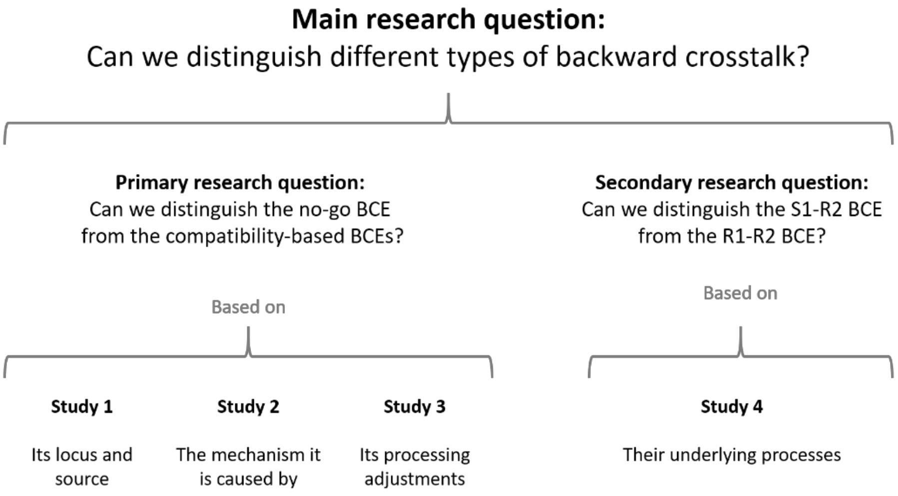

Figure 9. Illustration of the main research question and the subordinate research questions.

6 Studies

The research questions addressed by each of the studies carried out during the course of the present dissertation are illustrated in Figure 9. In the following, each study is summarized.

6.1 Study 1: The no-go BCE is located in motor execution

Evidence for the locus and source of the no-go BCE is still mixed. One line of reasoning suggests that in the case of a no-go trial an already prepared Response 2 has to be inhibited (Janczyk & Huestegge, 2017; Miller, 2006), and that this inhibition spills over from Task 2 response selection to Task 1 motor execution (Ko & Miller, 2014). Evidence from these studies suggest a model with the locus in Task 1 motor execution and the source in Task 2 response selection (see Figure 8). As an alternative, Röttger and Haider (2017) suggested that the no-go BCE is caused by (in)compatibility on a more abstract level because the "go representation" of Task 1 is incompatible to the "no-go representation" of Task 2 in a no-go trial. Thus, the perception of a no-go Stimulus 2 should automatically prolong RT1s in the same way the compatibility-based BCE is caused. Study 1 investigated whether the no-go BCE has its locus inside Task 1 motor execution or whether the no-go BCE is rather located in Task 1 response activation or central stage (and is thus based on similar cognitive mechanisms as the compatibility-based BCE).

In Experiment 1, the locus of slack logic was applied to distinguish whether the no-go BCE is located (1) before or (2) at or after the bottleneck (for the same reasoning applied to the compatibility-based BCE, see Janczyk, Renas et al., 2018, Experiment 1). To this end, three tasks were applied in a PRP-like paradigm. Stimulus 1 always arrived first and was followed by Stimulus 2 and 3 after a variable SOA of 50 vs. 1000ms. Task 1 required a vocal response ("tip" vs. "top") to a high or low tone, Task 2 required a manual response (left index vs. middle finger) to a blue or yellow letter, and Task 3 was a go/no-go task requiring a response with the right index finger or requiring no response to the identity of a “H” or “X”. Thus, Task 1 central stage created cognitive slack for the following tasks, Task 2 was the task in which the no-go BCE was observed, and Task 3 was the task causing the no-go BCE. At the long SOA of 1000ms a no-go BCE was expected to be obtained in Task 2 because a prolongation of any Task 2 stage would prolong RT2s equally (see Figure 10). At a short SOA of 50ms, an absence of the no-go BCE in Task 2 would indicate a locus before the bottleneck, as any prolongation of a stage before the bottleneck would be absorbed into slack without any chance to postpone the onset of subsequent stages. This should manifest in an underadditive pattern in RT2s. If, however, a no-go BCE is observed at the 50ms SOA, a locus at or after the bottleneck would be indicated, which would manifest in an additive pattern. Indeed, the RT2 pattern was additive which indicates that the no-go BCE has its locus in Task 2 response selection or motor execution (for an illustration see Figure 4 of the attached Study 1).

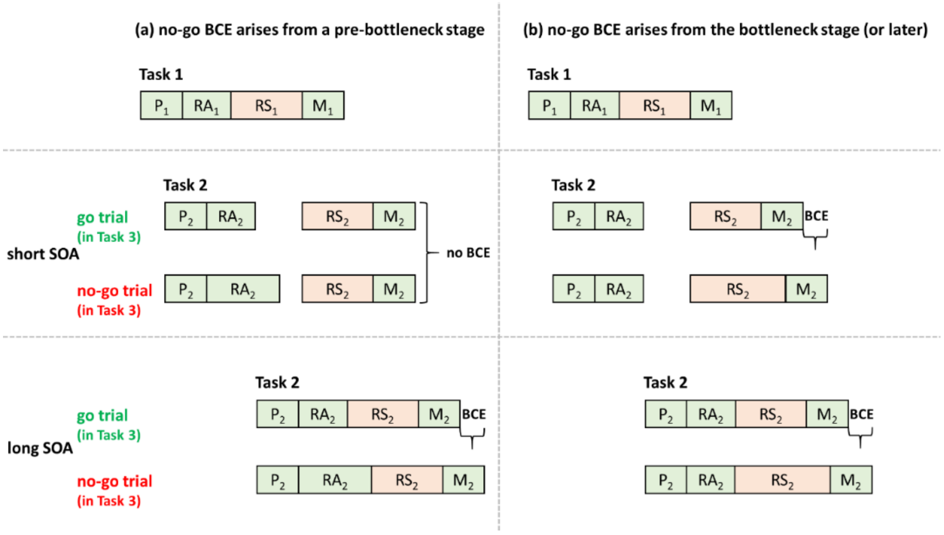

Figure 10. Illustration of the locus of slack logic applied in Experiment 1 of Study 1. (a) Illustration of the case where the no-go BCE arises in Task 2 response activation. (b) Illustration of the case where the no-go BCE arises in Task 2 response selection. Note, that the predictions for a prolonged motor execution stage are the same. (P = perceptual stage; RA = response activation; RS = response selection; M = motor stage; Task 3 has been omitted in this illustration)

In Experiment 2, a variant of the effect propagation logic was applied to distinguish between a locus (1) before or at the bottleneck or (2) after the bottleneck (for a similar reasoning applied to the compatibility-based BCE, see Janczyk, Renas et al., 2018, Experiment 4). To this end, the order of the tasks in Experiment 1 was reversed, and the two tasks which enabled the no-go BCE arrived first. Task 1 (the identity task) was the task in which the BCE was observed, while Task 2 (the color task) was the task causing the no-go BCE in Task 1. Both tasks were followed by Task 3 (the tone task) after the SOA. For the logic applied here, first only consider the 50ms SOA. It is important to note that the central stage in no-go trials is shorter than in go trials (de Jong, 1993; Van Selst & Johnston, 1997), which counteracts the propagation that would usually be expected in an effect propagation paradigm. If the no-go BCE is located in the central stage, two situations are possible: (1) Task 2 central stage is strongly shortened allowing an earlier onset of Task 3 central stage in no-go relative to go trials, and thus the no-go BCE observed in Task 3 would be inverted (see Figure 5a in the attached Study 1, left panel). (2) Task 2 response selection is moderately shortened leading to a reduction of the no-go BCE in Task 3 relative to Task 1 (see Figure 5b of the attached Study 1, left panel).

If the locus of the no-go BCE is in motor execution, the prolongation of this stage would only affect RT1. Thus, RT3s would be shorter in no-go relative to go trials, irrespective of the length of Task 2 central stage (see Figure 5a and 5b in the attached Study 1, right panel respectively). At the long SOA of 1000ms, RT3s should be unaffected by the go/no-go manipulation in Task 2.

In a nutshell, a propagation of the no-go BCE from Task 1 to Task 3 would indicate a locus in the central stage. An inverted no-go BCE, on the other hand, would be compatible with a locus in the central stage or in motor execution and thus would not allow to distinguish between both possible loci. Indeed, the no-go BCE in Task 3 was inverted at the 50ms SOA and not present at the 1000ms SOA, which could be interpreted as first evidence for a motor locus (see Figure 6 in the attached Study 1).

To corroborate this conclusion, a baseline condition was added against which the inverted no-go BCE in Task 3 of the triple-task condition could be compared in Experiment 3. In the baseline condition Task 1 of the triple-task was omitted. Thus, shorter RT3s in no-go relative to go trials – the inverted no-go BCE – could be entirely ascribed to the earlier onset of Task 3 response selection, excluding any influence of a possible propagation from Task 1. Likewise, under the assumption of a motor locus in the triple-task, the onset of Task 3 response selection and thus the size of the no-go BCE is not influenced by any propagation from Task 1. Thus, a motor locus would lead to the same size of the inverted no-go BCE in the triple task as in the dual-task baseline as illustrated in Figure 11. Under the assumption of a response selection locus, however, the onset of Task 3 response selection is delayed, leading to a smaller inverted no-go BCE as compared to the dual-task baseline. The number of tasks (triple- vs. dual-task condition) was manipulated block-wise and the integral stimulus for Task 1 and Task 2 was changed to two separate stimuli, to allow for an omission of Stimulus 1 without also omitting Stimulus 2 in the baseline condition. The white letter (Stimulus 1) was now surrounded by a colored square (Stimulus 2). The only change in the procedure, relative to Experiment 2, was the use of a constant SOA of 50ms was used. The size of the inverted no-go BCE did not differ between the triple-task condition and the dual-task baseline condition. Thus, the results

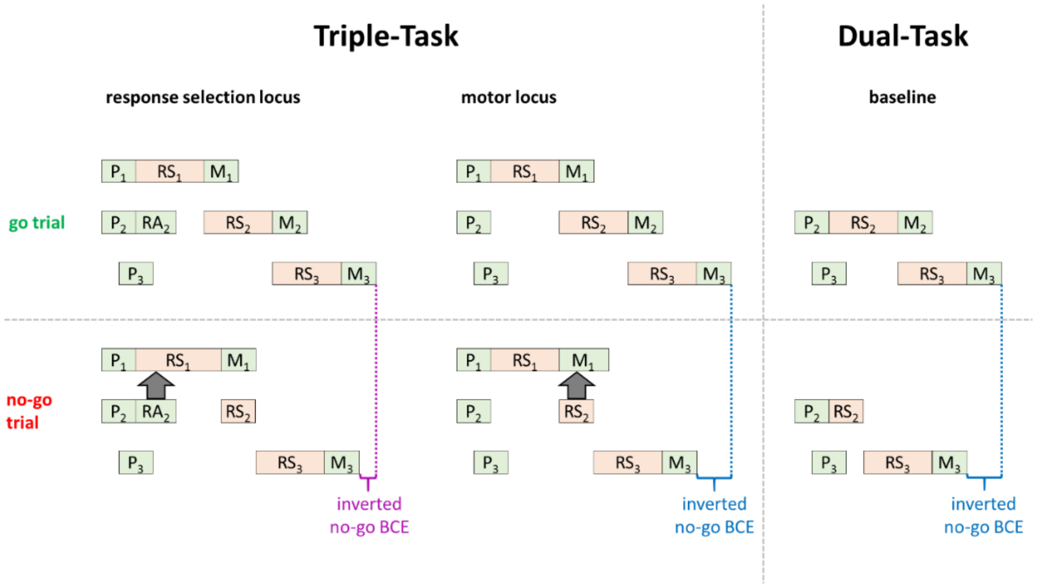

Figure 11. Illustration of the effect propagation logic applied in Experiment 3 of Study 1. The left side of the panel illustrates the predictions for the inverted no-go BCE in Task 3 for the triple-task condition. The predictions are based on the assumption of either a response selection or motor locus. The right side of the panel illustrates the prediction for the inverted no-go BCE in Task 3 for the dual-task baseline. (P = perceptual stage; RA = response activation; RS = response selection; M = motor stage; the subscript indicates Task 1, Task 2, and Task 3, respectively)

of Experiment 3 indicate that the no-go BCE is located inside motor execution (see Figure 8 in the attached Study 1).

Taken together, Experiment 1 ruled out a locus before the bottleneck, Experiment 2 provided first evidence for a locus in motor execution, and Experiment 3 ruled out a locus at or before the bottleneck and thus confirmed the locus inside Task 1 motor execution. A locus inside motor execution rules out the model suggested by Röttger and Haider (2017), which assumes the locus in Task 1 central stage and the source in Task 2 response activation. In general, it seems unlikely that the no-go BCE has its source in Task 2 response activation, as this stage does not temporally overlap with Task 1 motor execution. Against the background of the present results, the most plausible model is one assuming the locus in Task 1 motor execution and the source in Task 2 central stage (see Figure 8; Janczyk & Huestegge, 2017; see Miller, 2006, General Discussion for a tentative suggestion). Such a model differs qualitatively from the model for the compatibility-based BCE illustrated in Figure 4b which assumes a locus in Task 1 central stage and the source in Task 2 response activation (Janczyk, Renas et al., 2018; Thomson et al., 2015). While this model for the no-go BCE suggests that the no-go BCE is caused by a controlled process occurring during Task 2 central stage, the design of Study 1 does not allow to investigate the nature of this process. Against the background of what has been suggested by previous studies (Janczyk & Huestegge, 2017; Ko & Miller, 2014; Miller, 2006; Miller & Durst, 2014, 2015), it is conceivable that this process is the inhibition of an already prepared response. However, the inhibition hypothesis has not been tested directly. This was the purpose of Study 2.

6.2 Study 2: The no-go BCE is based on the inhibition of prepared responses

Study 2 aimed to test the inhibition hypothesis. To this end, a two-choice Task 1 was combined with a choice/no-go Task 2, which either required one of two manual go responses or a no-go response. The critical manipulation was the frequency of the Task 2 go-stimuli. In half of the blocks, both go-stimuli occurred equally often, which should not encourage participants to prepare a specific response in advance (unbiased blocks). In this case no, or even a reversed no-go BCE was expected (see also Janczyk & Huestegge, 2017, for this observation) because no Task 2 response was prepared, and thus no inhibition was needed to withhold the according response. In the other half of blocks, one go-stimulus occurred in 90% of all go-trials, which should encourage participants to prepare the according response in advance (biased blocks). In this case, the inhibition hypothesis predicts that the no-go BCE emerges, because the response prepared in advance has to be inhibited.

RTs in both tasks were shorter in biased relative to unbiased blocks, indicating that participants indeed prepared the more prepotent Task 2 response in advance (see Figure 2 of the attached Study 2). The no-go BCE was obtained in biased blocks, and it was even inverted in unbiased blocks. These results support the assumption that the inhibition of an already prepared response is the mechanisms that causes the no-go BCE.

6.3 Study 3: Distinguishing the no-go BCE from the compatibility-based BCEs: Evidence from the diffusion model

Taken together, the results of Studies 1 and 2 suggest that the no-go BCE can be distinguished from the compatibility-based BCE in several aspects: (1) The no-go BCE has its locus in Task 1 motor execution and its source in Task 2 response selection, and (2) the no-go BCE is caused by the inhibition of an already prepared Task 2 response. These results indicate that both BCEs are based on fundamentally different processes and that they are caused by different mechanisms, which suggests that both BCEs can actually be distinguished as two different types of BCEs. However, one aspect in which both BCEs can also potentially differ is the way in which previous trials influence the size of each BCE in the present trial – and thus, the way in which cognitive control adjusts processing in both BCEs.

Adjustment from cognitive control has frequently been assessed by sequential modulations, which is the influence of a previous trial on compatibility effects in the present trial. Recent studies observed that the size of compatibility-based BCEs in Trial *n* depended on the compatibility-status of the previous Trial *n*-1 (Janczyk, 2016; Renas et al., 2018; Scherbaum, Gottschalk, Dshemuchadse, & Fischer, 2015; see also Schuch, Dignath, Steinhauser, & Janczyk, 2019). In these studies, the compatibility-based BCE was present following compatible trials, whereas it was absent (or sometimes even reversed) following incompatible trials. The sequential modulations reported for the compatibility-based BCEs are similar to what was frequently observed in conflict tasks (Gratton, Coles, & Donchin, 1992; for evidence for the Simon effect see e.g., Praamstra, Kleine, & Schnitzler, 1999; see also Janczyk & Leuthold, 2018; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002) and they have frequently been interpreted as evidence for adaptation to just experienced conflict (for a review, see Egner, 2007). According to the conflict monitoring hypothesis (Botvinick, Braver, Barch, Carter, & Cohen, 2001), conflict registered in a trial leads to an optimized task processing in the following trial. It was suggested that the reduced compatibility-based BCE following incompatible trials is caused by shielding Task 1 against influences of Task 2 (Fischer, Gottschalk, & Dreisbach 2014; Janczyk, 2016). As an alternative, Task 2 response activation might become suppressed after incompatible trials, and thus Task 1 is less influenced by Task 2. While several studies observed sequential modulations for the compatibility-based BCE, so far no study assessed sequential modulations for the no-go BCE.

The goal of Study 3 was to (1) investigate sequential modulations for the no-go BCE, (2) to reveal the reasons for sequential modulations in both BCEs, and (3) to further test the models visualized in Figure 4b and 8. While behavioral data was sufficient to investigate sequential modulations of the no-go BCE, a diffusion model was fitted to these data to reveal the reasons for the sequential modulations in both BCEs and to test the models suggested for both BCEs.

The diffusion model (Ratcliff, 1978) is a mathematical model of human decision making in binary tasks (for an illustration see Figure 12). It assumes that a participant accumulates evidence for a decision until one of two decision thresholds is hit. When the decision threshold is reached, the decision is made and the according response is given. The standard diffusion model comprises three main parameters: The drift rate (v) reflects the speed and direction of the accumulation process, non-decision time (t_0) reflects the duration of processes occurring before and after the decision process (such as perceptual and motor processes), and threshold separation a reflects the amount of information needed to reach a decision. The accumulation process usually starts between both thresholds. From there, drift rate drives the information into one direction, while random noise is added. This random noise causes the accumulation process to reach the correct threshold at varying points in time, and can also cause the diffusion process to reach the wrong threshold leading to an error.

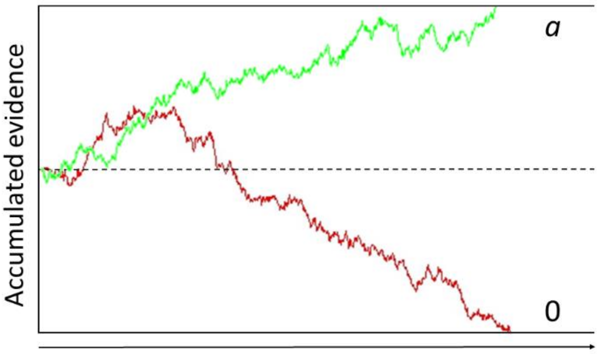

Figure 12. Exemplary illustration of decision processes in the diffusion model. The two thresholds (here associated with correct [*a*] and erroneous responses [0]) are separated by the threshold separation *a*. The accumulation process moves with drift rate *v* from the starting point (here centered between thresholds) until it reaches the upper or lower threshold. To the decision process depicted in the figure add non-decisional processes (e.g., encoding of information, motoric response execution). The green line illustrates a decision process leading to a correct response and the red line illustrates a decision process leading to a wrong response.

In the following, I will present the hypotheses separately for both BCEs and for behavioral measures and diffusion model parameters of Task 1, starting with the **compatibility-based BCEs.** For the behavioral measures, a sequential modulation signified by a larger BCE following compatible relative to incompatible trials was expected (e.g., Janczyk 2016). As the compatibility-based BCEs are located in the central stage (Janczyk, Renas et al., 2018; Thomson et al., 2015), and because v is known to be larger in compatible relative to incompatible trials (Janczyk, Mittelstädt, & Wienrich, 2018), sequential modulations in behavioral data were expected to be reflected in sequential modulations of v.

For the **no-go BCE** a sequential modulation in the behavioral data was expected, with a no-go BCE only following go trials. Against the background of Study 1 and 2, it was assumed that participants would adjust their preparation state in Trial n according to the nature of Trial n-1. This means that following go-trials participants would again prepare the Task 2 response, which should lead to a no-go BCE in case of a no-go trial. Following no-go trials, however, the Task 2 response should not be prepared, and thus no no-go BCE should be observed, as there is nothing to inhibit. Against the model suggested in Study 1 (see Figure 8), the sequential modulation was predicted to be reflected in a sequential modulation of t_0.

By and large, the predicted results were obtained (see Figures 4, 6, and 10 in the attached Study 3). For the compatibility-based BCEs a sequential modulation was observed in the behavioral data and in the diffusion model parameter v. [4] These results support the model assuming that the compatibility-based BCEs have their locus inside Task 1 central stage and their locus in Task 2 response activation (see Figure 4b; Janczyk, Renas et al., 2018; Thomson et al., 2015). Parameter effects for Task 2 were either absent, small, and/or unreliable, and thus

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[4] As an additional, albeit subsidiary, hypothesis, an interaction of compatibility in Trial n and Trial n-1 was predicted for t_0. This prediction is due to the trial to trial transitions from incompatible to incompatible and compatible to compatible trials, which entail 50% of exact repetitions of the same two responses (see also Figure 1 in Janczyk, 2016). Such exact repetitions can lead to shorter RTs due to re-usage of motor programs (e.g., Rosenbaum, Weber, Hazelett, & Van Hindorff, 1986). This interaction was indeed observed and thus data from Experiment 3 in Janczyk (2016), where the aforementioned transitions were avoided, were reanalyzed. As was expected the sequential modulation in v was replicated, but not in t_0.

the present results are in line with the assumption that Task 2 was not suppressed. Rather, following an incompatible trial, Task 1 is shielded against influences of Task 2.

For the no-go BCE, a sequential modulation was observed in the behavioral data and in t_0. This supports the model suggested in Study 1, assuming that Task 1 motor execution is the locus and Task 2 central stage is the source of the no-go BCE (see Figure 8). For Task 2, RTs were shorter following go than no-go trials and v was larger following go than no-go trials. These results support the assumption that Response 2 preparation was increased following go trials.

In a nutshell, the results of Study 3 provided converging evidence for a qualitative distinction of the compatibility-based BCEs and the no-go BCE, as both BCEs appear to have different loci and sources. Furthermore, both BCEs differ fundamentally in the way cognitive control is adjusted. While in the compatibility-based BCE, cognitive control appears to adjust shielding of Task 1 from influences of Task 2, in the no-go BCE cognitive control seems to adjust the preparation state for Response 2.

6.4 Study 4: Distinguishing two types of compatibility-based backward crosstalk

Studies 1-3 provided evidence that the compatibility-based BCEs differ qualitatively from the no-go BCE. However, it is also conceivable that two types of compatibility-based BCEs, namely the R1-R2 BCE and the S1-R2 BCE, differ qualitatively, as they result from different types of dimensional overlap. The R1-R2 BCE is based on spatial overlap of response features, whereas the S1-R2 BCE is based on overlap of stimulus and response features. Further, it should be noted that in Experiment 3 of Janczyk, Renas et al. (2018) a descriptive trend towards underadditivity was obtained for the S1-R2 BCE, which suggests that the S1-R2 BCEs could actually arise in the perceptual instead of central stage. Therefore, it remains possible that both compatibility-based BCEs are based on different processes. Study 4 investigated whether both compatibility-based BCEs indeed arise in the central stage (see Janczyk, Renas et al., 2018), and whether they are based on the same or different processes in three experiments.

If both BCEs would not be located in the same processing stage, different underlying processes for both compatibility-based BCEs would be indicated. Experiment 1 investigated whether either the R1-R2 BCE or the S1-R2 BCE have a precentral locus. To this end the brightness of Stimulus 1 was varied trial-by trial in blocks of R1-R2 BCE tasks and S1-R2 BCE tasks. In general, longer RTs for trials with a dark relative to bright Stimulus 1 were expected. The main hypothesis was based on Sternberg's (1969) additive factors logic: A significant interaction of two experimental factors indicates that both factors affect the same processing stage, whereas an additive combination of both factors is more in line with the assumption that two different processing stages are affected. As the R1-R2 BCE is located in the central stage, the manipulation of a perceptual feature like Stimulus 1 brightness should not modulate the R1-R2 BCE. Accordingly an additive combination of Stimulus 1 brightness and R1-R2 compatibility status was expected. For the S1-R2 BCE, a significant interaction of S1-R2 compatibility status with Stimulus 1 brightness would indicate that the S1-R2 BCE arises in the perceptual instead of central stage. If, however, S1-R2 compatibility status does not interact with Stimulus 1 brightness, a locus in the perceptual stage can be ruled out for the S1-R2 BCE. As predicted, longer RT1s were observed when Stimulus 1 was dark relative to bright. Crucially, Stimulus 1 brightness only combined additively with both BCEs (see Figure 2 of the attached Study 4), and thus results of Experiment 1 indicate that both compatibility-based BCEs arise in the *same* processing stage, namely the capacity-limited central stage of processing (Janczyk, Renas et al., 2018).

However, it is still conceivable that different capacity-limited processes underlie both compatibility-based BCEs (see Hommel, 1998, p. 1374). Experiments 2 and 3 asked whether this is the case. To this end, the R1-R2 BCE and the S1-R2 BCE were both enabled in each trial to investigate sequential modulations within and between both compatibility-based BCEs. While sequential modulations within each compatibility-based BCE were expected (even though they have not yet been demonstrated for the S1-R2 BCE), possible sequential modulations between both compatibility-based BCEs were of main interest. For the main hypothesis, consider a model in which the central stage comprises two subsequent capacity-limited processes, each responsible for one of the BCEs. Such a model assumes that a capacity-limited process should only be adjusted in Trial *n* if the same process was subject to conflict in the previous Trial *n*-1. Precisely, a sequential modulation of a particular BCE should only occur, if the compatibility status of the same BCE was incompatible in Trial *n*-1. Thus, if only sequential modulations within each BCE would be obtained, two different processes for both compatibility-based BCEs would be indicated. Mutual sequential modulations of both compatibility-based BCEs, however, would indicate that both compatibility-based BCEs are based on the same capacity-limited process and that the model should be rejected.

To facilitate mutual sequential modulations, stimulus and response features for both BCEs were kept as similar as possible (Braem, Abrahamse, Duthoo, & Notebaert, 2014). In each trial, the letters “H” and “S”, colored in red or green, were presented above or beneath the screen center (for an illustration of the trial structure, see Figure 13). In Experiment 2, the position of the letter served as Stimulus 1, the identity of the letter served as Stimulus 2, and the color served as response-cue for the response to Stimulus 2. Participants were instructed to first respond to Stimulus 1 in a pedal two-choice task, and to subsequently respond to Stimulus 2 in a manual two-choice task by pressing an upper or lower key. There was an upper and lower key on each side of the participant, and a home-key was placed between the response-keys on both sides. The home-keys were to be kept pressed from the beginning of the trial. The side on which the upper or lower key had to be pressed was determined by the color of the letter. The participants were instructed to let go of the respective home-key when they decided which key to press on the according side. A trial was considered R1-R2 compatible when the pedal and manual response were given on the same side (e.g., a left pedal response and a left manual response), whereas a trial was considered R1-R2 incompatible when both responses were given on different sides (e.g., a left pedal response and a right manual response). Thus, the color determined R1-R2 compatibility in Trial *n*. A trial was considered S1-R2 compatible when the letter location and the location of the response matched (e.g., a letter presented above fixation and a response with an upper key), whereas a trial was considered S1-R2 incompatible when the letter location and the location of the response did not match (e.g., a letter presented above fixation and a response with a lower key). The only change in Experiment 2 was that the color now determined S1-R2 compatibility, instead of R1-R2 compatibility (for an illustration of the trial structure, see Figure 13).

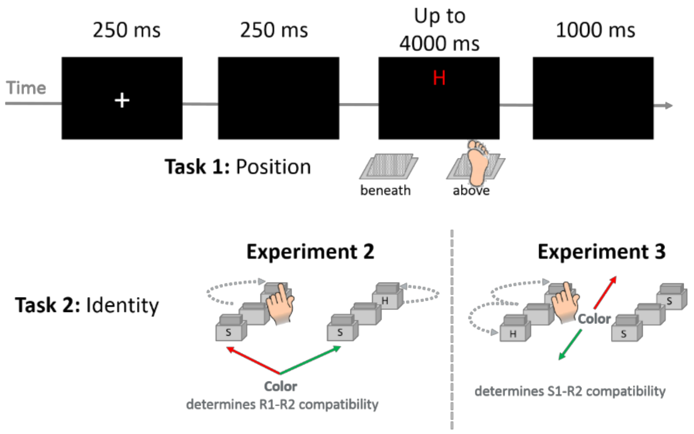

Figure 13. Graphical illustration of the trial structure and the tasks in Experiment 2 and Experiment 3 of Study 4. In Experiment 2 the color cue determines R1-R2 compatibility, whereas in Experiment 3 the color cue determines S1-R2 compatibility.

By and large, very similar results were obtained in Experiment 2 and 3. As expected, sequential modulations within each BCE were present. Most importantly, in both experiments *no* mutual sequential modulations of both BCEs were obtained (see Figures 7 and Figure 9 in the attached Study 4). This result suggests that both compatibility-based BCEs are based on different processes, and is thus in line with a model assuming two (subsequent) capacity-limited processes in the central stage (see Figure 15). In other words, if conflict is experienced in one of both BCEs in Trial *n*-1, the process responsible for the respective BCE is adjusted in Trial *n*. However, at this point the true nature of these two processes remains unknown.

Against the background of previous studies, it is conceivable that the R1-R2 BCE is based on the central process of response selection, which receives the activation resulting from automatic stimulus-response translation in the Task 2 response activation stage (for behavioral evidence, see Janczyk, Renas et al., 2018; Thomson et al., 2015; for evidence from the LRP, see Lien et al., 2007; Miller, 2017). For the S1-R2 BCE, this assumption is implausible, as this BCE is based on the overlap of Stimulus 1 with Response 2. Instead, it appears plausible that a process responsible for Stimulus 1 processing receives the stimulus-response translation resulting from Task 2 response activation (for a similar suggestion see, Hommel, 1998, p. 1374).

Taken together, results of Study 4 support the assumption that the R1-R2 BCE and the S1-R2 BCE are located in the capacity-limited stage. However, both compatibility-based BCEs appear to be based on two different capacity-limited processes. In the General Discussion, I will suggest a model that can account for both compatibility-based BCEs.

7 General Discussion

Dual-tasking, that is performing more than one task in close temporal succession, is known to lead to decrements in the performance of both tasks involved compared to when they are performed in isolation. The decrements arising in the second of two subsequently performed tasks have frequently been explained with a structural bottleneck in human cognition. This bottleneck only allows central processing for one task at a time, while processing of the other must wait until the bottleneck is available again. However, this widely accepted view of strictly serial processing in dual-tasking has recently been challenged by observations, in which aspects of Task 2 already influenced performance of Task 1, even though Task 2 was still waiting for access to the bottleneck. Such backward crosstalk effects can, for instance, be observed when features of Task 1 overlap with features of Task 2 – the compatibility-based BCEs – but also when no dimensional overlap between both tasks is given, as is the case the no-go BCE.

The main question of the present dissertation was: Can we distinguish different types of backward crosstalk? To address this question, the following two subordinate research questions were answered in Studies 1-4 (see Figure 9). The primary research question was: Can we distinguish the no-go BCE from the compatibility-based BCEs, based on its underlying cognitive processes (Study 1), the mechanism it is caused by (Study 2), and the way in which characteristics of the previous trial lead to processing adjustments in the present trial (Study 3)? The secondary research question was: Can we distinguish the S1-R2 BCE from the R1-R2 BCE based on their underlying processes (Study 4)?

In the following, I will first answer the primary research question based on the results of Studies 1-3. Then I will answer the secondary research question and suggest a model that can account for both compatibility-based BCEs based on the results of Study 4. To anticipate, all these studies indicate that different types of backward crosstalk should be distinguished. Subsequently, I will discuss in how far backward crosstalk effects and related phenomena can be integrated. I will continue with implications for theories of dual-tasking and end with a general conclusion regarding the main research question.

7.1 Summary of results

7.1.1 Can the no-go BCE be distinguished from the compatibility-based BCE?

Studies 1, 2, and 3 were dedicated to distinguish the no-go BCE from the compatibility-based BCE. Study 1 aimed to distinguish the no-go BCE from the compatibility-based BCE based on its underlying locus and source. Applying the locus of slack and effect propagation logic, the locus of the no-go BCE was identified in motor execution of Task 1. The most plausible model that can account for the no-go BCE is one that assumes that the no-go BCE has its locus in Task 1 motor execution and its source in Task 2 central stage (for an illustration see Figure 14a; for a similar suggestion see, Janczyk & Huestegge, 2017; see Miller, 2006, General Discussion for a tentative suggestion). Such a model implies that the no-go BCE is enabled when Task 1 motor execution and Task 2 central stage temporally overlap and thus the no-go BCE differs qualitatively from the compatibility-based BCEs, which have their locus in Task 1 central stage and their source in Task 2 response activation (see Figure 14b; Janczyk, Renas et al., 2018; Thomson et al., 2015). If in a no-go trial temporal overlap is given between Task 1 motor execution and Task 2 central stage, a controlled process in Task 2 central stage causes the no-

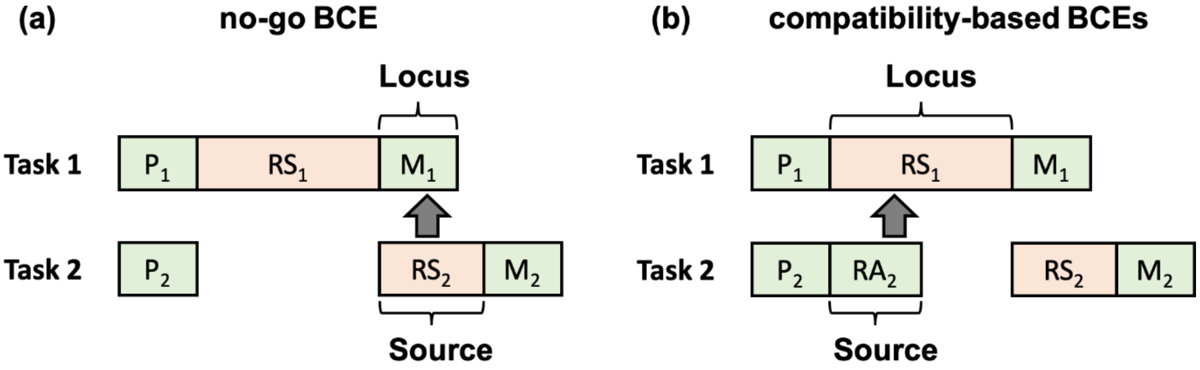

Figure 14. Illustration of the locus and the source of the (a) no-go BCE and the (b) compatibility-based BCEs (Janczyk Renas et al., 2018; Thomson et al., 2015). (P = perceptual stage, RS = response selection, RA = response activation, M = motor stage, the subscript indicates Task 1 and 2, respectively).

go BCE in Task 1. Several studies suggested that this controlled process is the inhibition of an already prepared Response 2 spilling over to Task 1 (Janczyk & Huestegge, 2017; Ko & Miller, 2014; Miller, 2006; Miller & Durst, 2014, 2015).

Study 2 examined whether an overspill of inhibition, needed to overcome an already prepared Response 2, is the mechanism that causes the no-go BCE. To this end, preparation for one of two go-responses of a two-choice/no-go Task 2 was either encouraged in biased blocks or was not encouraged in neutral blocks, where the no-go BCE was even inverted (see also Janczyk & Huestegge, 2017, for this observation). This suggests that no inhibition occurred in no-go trials, as the unprepared Response 2 did not have to be inhibited. As predicted, the no-go BCE reemerged in biased blocks. This supports the assumption that in no-go trials inhibition is recruited to withhold an already prepared Response 2. Against the background of the model suggested in Study 1, results of Study 2 deliver first behavioral evidence that the mechanism causing the no-go BCE is indeed the inhibition of a prepared Response 2 spilling over to Task 1. Note that this can be taken as further evidence against the alternative model suggested by Röttger and Haider (2017). In a similar vein, the present results help to further distinguish the no-go BCE from the compatibility-based BCEs, which are assumed to be caused by automatic-response feature activation occurring in Task 2 (e.g., Hommel, 1998; Janczyk, Renas et al., 2018; Lien & Proctor, 2000; Thomson et al., 2015).

The results of Study 1 and 2 suggest that the no-go BCE differs from the compatibility-based BCEs not only in its locus and source, and thus in its underlying cognitive processes, but also in the mechanism it is caused by. As a consequence, two different models are needed to account for both types of BCEs. To further test the validity of the model suggested for the no-go BCE in Study 1 and the model for the compatibility-based BCEs (Janczyk, Renas et al., 2018, Thomson et al., 2015), Study 3 employed the diffusion model. Additionally, this approach allowed to further delineate the no-go BCE from the compatibility-based BCEs based on the way processing is adjusted depending on characteristics of the previous trial, as sequential modulations of the model parameters can be interpreted as indicators for the respective processing stage in which the adjustment is made. For the no-go BCE sequential modulations were expected to be reflected in non-decision time t_0. For the compatibility-based BCEs, recent evidence suggests that sequential modulations should be reflected in drift rate v, as these BCEs have their locus in the central stage (Janczyk, Renas et al., 2018; Thomson et al., 2015; for first evidence from the diffusion model see, Janczyk, Mittelstädt et al., 2018). Indeed, for the no-go BCE sequential modulations were reflected in t_0, whereas the sequential modulations of the compatibility-based BCE were reflected in v. These results are in line with the models that were suggested for the no-go BCE (Figure 14a) and for the compatibility-based BCEs (Figure 14b). Thus, the present results provide additional evidence for a qualitative distinction of the no-go BCE and the compatibility-based BCE based on their underlying processing stages.

Data for Task 2 of Study 3 allowed for a first exploratory investigation of how characteristics of the previous trial lead to processing adjustments in both types of BCEs. For the compatibility-based BCE cognitive control could adjust two – not necessarily mutually exclusive – mechanisms of shielding Task 1 from influences of Task 2 (e.g., Fischer et al., 2014; Janczyk, 2016), and suppression of Task 2 response activation (similar to what has been suggested to occur in standard conflict tasks; e.g., Janczyk & Leuthold, 2018; Stürmer et al., 2002; Stürmer & Leuthold, 2003). However, Task 2 diffusion model parameter data were not that clear cut. As Task 2 processing was unaffected, it can tentatively be suggested that Task 2 response activation was not suppressed. Instead, results for Task 2 rather suggest that Task 1 processing was adjusted, which is in line with the notion that Task 1 is shielded. It should be noted that the concept of task shielding is still underspecified, as it is unknown how exactly task shielding alters processing of both tasks. Future studies should investigate whether the concept of task shielding could be specified or maybe even entirely replaced by the concept of task-set activation (Goschke, 2003, Dreisbach & Haider, 2008, 2009), increased attention allocated to Task 1 (similar to how Botvinick et al., 2001, conceptualized cognitive control to operate in the Stroop task), or a facilitated perceptual processing in Task 1 (Stelzel, Brandt, & Schubert, 2009).

Processing adjustment via task shielding appears implausible for the no-go BCE, as its locus is in motor execution. Instead, it seems reasonable to assume that sequential modulations of the no-go BCE depend on the preparation state for Response 2. According to this assumption, participants would continue to prepare Response 2 following go trials, whereas following no-go trials preparation for Response 2 should be decreased or even absent. These assumptions were supported by the observations that RT2s where shorter following go relative to no-go trials and that v was larger following go than no-go trials. This suggests that indeed the status of Response 2 preparation is either “prepared” (following go trials) or “unprepared” (following no-go trials) in an all or nothing manner in the no-go BCE. The notion of this all or nothing adjustment, however, is in contrast to the assumption that cognitive control scales processing adjustments continuously, depending on the degree of just experienced conflict (Botvinick et al., 2001, p. 630). This raises the question whether cognitive control even adjusts the preparation state for Response 2, or whether such adjustments can be made more efficiently by simply re-using the motor programs needed in the previous trial. Taken together, results for Task 2 of Study 3 indicate that compatibility-based BCEs and the no-go BCE differ in the way processing adjustments are made. In the compatibility-based BCEs task processing is presumably adjusted by shielding of Task 1, whereas in the no-go BCE the preparation state for Response 2 seems to be adjusted. However, future studies are needed to investigate whether cognitive control is involved in the latter adjustments.

To conclude, the answer to the primary research question is: Indeed, the no-go BCE can be distinguished from the compatibility-based BCE, as it differs in its underlying processing stages, in the mechanism it is caused by, and in the way processing is adjusted depending on characteristics of the previous trial.

7.1.2 Can the S1-R2 BCE be distinguished from the R1-R2 BCE?

While Studies 1-3 showed that the no-go BCE can be clearly distinguished from the compatibility-based BCEs, Study 4 aimed to distinguish two types of compatibility-based BCEs, namely the S1-R2 BCE and the R1-R2 BCE. To this end, Experiment 1 of Study 4 applied Sternberg's (1969) additive factors logic to rule out a perceptual locus of both BCEs. As both BCEs were not modulated by the manipulation of Stimulus 1 brightness, results of Experiment 1 suggest that they do not have their locus in the perceptual stage, but most likely in the capacity-limited central stage as was suggested by Janczyk, Renas et al. (2018).

The following Experiments 2 and 3 investigated whether the same capacity-limited process underlies either compatibility-based BCE or whether both compatibility-based BCEs are based on two different capacity-limited processes. To this end, both the S1-R2 BCE and the R1-R2 BCE were enabled in the same trial. Cognitive control in one of two possible capacity-limited processes should only be adjusted in Trial *n* if the same process was subject to conflict in the previous Trial *n*-1. Following this logic, mutual sequential modulations of both compatibility-based BCEs would indicate that they are based on the same capacity-limited process. However, in Experiment 2 and 3 only sequential modulations *within* each compatibility-based BCE were observed, which is in line with the assumption that the S1-R2 BCE and the R1-R2 BCE are based on *different* capacity-limited processes.

For the R1-R2 BCE, several studies suggested that it is based on the central process of response selection, which receives the activation resulting from automatic stimulus-response translation in the Task 2 response activation stage (for behavioral evidence, see Janczyk, Renas et al., 2018; Thomson et al., 2015; for evidence from the LRP, see Lien et al., 2007; Miller, 2017). In the case of the S1-R2 BCE, however, automatic stimulus-response translation cannot influence Response 1 processing, as there is no dimensional overlap with Response 2. Instead, the S1-R2 BCE relies on conceptual or spatial overlap between Stimulus 1 and Response 2.

For the following explanation of the S1-R2 BCE, consider an experiment in which the letters H and S are presented in the color red or green. The color requires a manual response with the left or right index finger (Task 1) and the identity of the letter requires a vocal utterance of the words "red" or "green" (Task 2; see also Hommel, 1998, Experiment 2). In this case, Stimulus 2 – the letter identity – leads to the activation of a color word response (e.g., the Stimulus "H" is translated into the vocal utterance "red"). The activation of the color word response could then add to a process running in the capacity-limited central stage of Task 1. It is unlikely that response selection proper receives the activation of the color word and adds it to the activation of the manual response. Instead, it appears plausible that the activation of the color word feeds into an earlier capacity-limited process that deals with Stimulus 1 processing (for a similar suggestion, see Hommel, 1998, p. 1374).

One possible candidate for such a capacity-limited process is stimulus categorization, which categorizes the task relevant feature of Stimulus 1. This appears plausible for two reasons: (1) „higher level perceptual processing (such as stimulus classification)" (Johnston & McCann, 2006, p. 699) has been shown to be capacity-limited and (2) semantic category-response rules instead of stimulus-response rules appear to be held in working memory for the S1-R2 BCE (Ellenbogen & Meiran, 2008) and can also replace stimulus-response rules for the R1-R2 BCE under certain circumstances (Thomson et al., 2010). While (1) supports the assumption that stimulus categorization is indeed a capacity-limited process, (2) suggests that stimulus categorization is a process that occurs for both compatibility-based BCEs.

For the example of the S1-R2 BCE mentioned before, this means that *stimulus categorization* categorizes the task relevant feature of Stimulus 1 as red or green (see Figure 15). If stimulus categorization of Task 1 temporally overlaps with response activation of Task 2, activation of the color word derived from Task 2 response activation feeds into stimulus categorization running in Task 1 central stage. If Stimulus 1 and Response 2 are compatible, the color word activation added to stimulus categorization activates the respective color-category of Stimulus 1, and thus the categorization process is completed faster compared to Stimulus 1 and Response 2 being incompatible. The task relevant feature of Stimulus 1 is then translated into the correct response by the process of response selection. For the R1-R2 BCE the stimulus categorization model assumes that the activation of a certain response feature in Task 2 response activation feeds into the process of response selection as already suggested by the model proposed by Janczyk, Renas et al. (2018) and Thomson et al. (2015). This is because the Response 2 feature only spatially overlaps with the response into which Stimulus 1 is translated by response selection, and not with Stimulus 1 categorized in stimulus categorization.

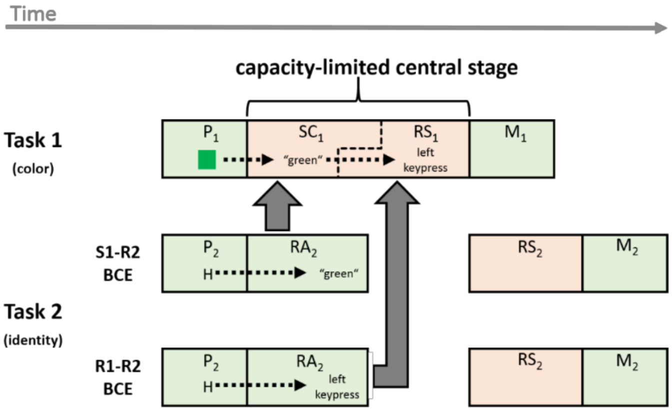

Figure 15. The stimulus categorization model. The capacity-limited central stage (orange) comprises two processes separated by a dashed line. Task 2 (the identity task) is illustrated separately for the S1-R2 BCE and the R1-R2 BCE. (P = perceptual stage, M = motor stage, the subscript indicates Task 1 and 2, respectively)

At this point, it cannot be safely said whether the two capacity-limited processes of stimulus categorization and response selection proceed in serial or (at least partially) in parallel. On the one hand it is plausible that stimulus categorization begins first, or at least gets a head start, as response selection needs to know which stimulus code needs to be translated into a response. On the other hand, it is possible that response selection runs (at least partially) in parallel with stimulus categorization. Two predictions can be derived from these assumptions. Under the assumption of two serial processes, the duration of each capacity-limited processes should be unaffected by the duration of the respective other capacity-limited process, and thus both compatibility-based BCEs should combine additively. Alternatively, if both processes (at least partially) run in parallel, the duration of both capacity-limited processes should depend on each other (see additive factors logic, Sternberg, 1969). For instance, if both processes run in parallel and one process is finished earlier in a compatible trial, the remaining process gains all available resources and is thus also finished earlier. [5] In fact, in Experiment 2 and 3 of Study 4 the interaction of both compatibility-based BCEs in Trial *n* was *not* significant. This indicates that the duration of both capacity-limited processes did not affect each other, and is thus in line with the assumption that both capacity-limited processes run in serial.

In a nutshell, results of Study 4 indicate that the S1-R2 BCE and the R1-R2 BCE both arise in the capacity-limited central stage, but they differ qualitatively in the capacity-limited process they are based on. Against the background of previous evidence, the stimulus categorization model was suggested, which can account for both compatibility-based BCEs. The stimulus categorization model assumes that the capacity-limited process of stimulus categorization underlies the S1-R2 BCE and presumably precedes the capacity-limited process of response selection that underlies the R1-R2 BCE. Future research is needed to directly test the stimulus categorization model.

7.2 Towards an integration of backward crosstalk effects and related phenomena

The results of Study 1-4 emphasize that observations of backward crosstalk arising under different preconditions differ qualitatively in several aspects such as their locus and source, the mechanism they are caused by, and in the way processing is adjusted depending on

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[5] At this point, it cannot be ruled out that both processes run completely in parallel and gain 50% of the available resources each. However, even a completely balanced allocation of resources to both processes would lead to the predicted interaction, as one of both processes likely finishes first.

characteristics of the previous trial (for a more comprehensive list of aspects see the first column of Table 2). Based on these aspects, phenomena related to the BCEs can be compared to the BCEs under investigation here. If a related phenomenon is similar to a BCE in a sufficient amount of aspects, an integration of both phenomena may be considered. In the following, I will undertake a first approach towards such an integration of the related phenomena mentioned in the introduction with the BCEs under investigation here. I will begin with the category match effect followed by the response congruency effect, and motor-related phenomena.

Table 2. Overview of the different types of BCEs and related phenomena (columns). Each row represents an aspect in which the phenomena differ. Matching colors indicate that the respective phenomena appear to be related to the types of BCEs under investigation here, according to the similarity of their aspects. Aspects that have not yet been investigated in the literature are labeled with a "?".

	Compatibility-based BCEs		**No-go BCE**		**Related phenomena**			
	R1-R2 BCE	**S1-R2 BCE**			**Category match effect**	**Response congruency effect**	**Complexity-based BCE-like effect**	**Force-based BCE-like effect**
Manifestation	RT1	RT1	RT1		RT1	RT1	RT1	Response 1 force
Overlap	Spatial	Conceptual / Spatial	-		Categorial	Spatial (?)	-	-
Locus	T1 central stage	T1 central stage	T1 motor execution		T1 central stage (?)	T1 central stage (?)	T1 motor execution	T1 motor execution
Source	T2 response activation	T2 response activation	T2 central stage		T2 response activation	T2 response activation (?)	T2 central stage	T2 central stage
Mechanism	Automatic response-feature activation	Automatic response-feature activation	Inhibition of a prepared Response 2		Automatic memory retrieval	Automatic response-feature activation (?)	Anticipation of response selection difficulty (?)	Anticipation of Response 2 force (?)
Processing adjustment	Task 1 shielding	Task 1 shielding	Preparation state for Response 2		Task 1 shielding (?)	Activation setting for both task sets	?	?
Response-rules in working memory	Category-response rules	Category-response rules	?		Category-response rules	Response-rules not held in working memory	?	?

7.2.1 The category match effect compared with BCEs.

Similar to the compatibility-based BCEs, the category match effect appears to be based on dimensional overlap, as RTs in Task 1 are shorter when stimuli of both tasks are of the same relative to different category. Indeed, Fischer et al. (2007) suggested that the category match effect has similar underlying cognitive preconditions as the compatibility-based BCEs (for additional evidence, see Oriet et al., 2005). These authors obtained evidence for semantic memory retrieval in Task 2 running in parallel with Task 1 central stage, applying the locus of slack logic to Task 2. While this suggests a source prior to the central stage, similar to the compatibility-based BCEs (Janczyk, Renas et al., 2018; Thomson et al., 2015), it, on the other hand, suggests that the mechanism causing the category match effect differs from the mechanism causing the compatibility-based BCEs. In line with what results of Study 3 suggest for the compatibility-based BCEs, it was suggested that cognitive control adjusts shielding of Task 1 in the category match effect (Fischer et al., 2014). However, it should be noted that these authors only interpreted the size of the category-match effect as an index for shielding of Task 1 and they did not investigate sequential modulations for the category match effect. Similar to the compatibility-based BCEs, Thomson et al. (2010) obtained evidence that the category match effect relies on category-response rules held in working memory.

In sum, the available evidence for the category match effect suggests that it has a similar source as the compatibility-based BCEs, and that for both phenomena similar response rules are held in working memory. However, at this point it is impossible to distinguish or integrate both phenomena, as evidence from studies directly comparing both phenomena lacks. A first step to bridge this gap would be to identify the model for the category match effect, applying the locus of slack and effect propagation logic (see Janczyk, Renas et al., 2018). If the model for the category match could not be distinguished from the model for the compatibility-based BCEs in such a study, this would support the assumption that both phenomena are qualitatively similar. Besides behavioral approaches directly investigating sequential modulations, it would also be insightful to apply computational models like the diffusion model (Ratcliff, 1978; see also Study 3 of the present dissertation) or the DMC (Ulrich et al., 2015), as well as psychophysiological approaches to verify that both phenomena have a common locus and source and that cognitive control adjusts processing similarly. If more evidence for qualitative similarities between both phenomena could be obtained, it might make sense to integrate the category match effect and compatibility-based BCEs under a common label (for a similar suggestion see, Fischer et al., 2007, p. 1696).

7.2.2 The response congruency effect compared with BCEs.

At first glance, the congruency effects in task switching appear to be based on spatial overlap of the responses required by both tasks and thus appear to be closer related to the compatibility-based BCEs than to the no-go BCE. Importantly, the observation that the irrelevant task influences performance of the relevant task in task switching is in line with the result that compatibility-based BCEs can even be obtained when Task 2 does not have to be carried out (for evidence from the S1-R2 BCE, see Hommel 1998, Experiment 5; for evidence from the R1-R2 BCE, see Janczyk, Renas et al., 2018, Experiment 2). Even though it appears plausible to assume that the response congruency effect has its source in Task 2 response activation (for a tentative suggestion, see Kiesel et al., 2007), evidence from studies investigating the locus, the source, and the mechanism causing the response congruency effect still lacks at this point.

Concerning processing adjustments, it was suggested that in the case of an incongruent stimulus the task-relevant set is strengthened, whereas the task-irrelevant task-set is inhibited (Goschke, 2000). Then, the just acquired activation setting for both task-sets is re-used in the following trial. Such a notion appears to share similarities with the processing adjustments made for the compatibility-based BCEs and with the prevalence of the preparation state for Response 2 in the no-go BCE. On the one hand, the activation setting seems to be adjusted continuously (for a tentative suggestion see Brown, Reynolds, & Braver, 2007, p. 72) similar to what would be assumed for the compatibility-based BCEs according to Botvinick et al. (2001, p. 630). On the other hand, the re-usage of activation settings is similar to the notion of re-used motor programs for the no-go BCE. However, at this point attempts to relate processing adjustments in the response congruency effect to compatibility-based BCEs and the no-go BCE remain highly speculative.

One aspect in which the response congruency effect appears to differ from the compatibility-based BCEs is in its response-rules, which are not held in working memory (Kiesel et al., 2007). Rather, such rules seem to be "formed during the experiment as participants repeatedly perform a particular response according to a given stimulus" (Kiesel et al., 2007, p. 123).

At this point, an integration of the response congruency effect with BCEs appears impossible, as these phenomena have never been directly compared in regard to the aspects listed in Table (2). Nevertheless, it should be noted that these phenomena are potentially related. Future studies directly comparing these phenomena are needed, to allow for an integration or a distinction of the response congruency effect and BCEs.

7.2.3 Motor-related phenomena compared with BCEs.

Miller (2006, Experiment 3) obtained longer RT1s when Task 2 required a triple index-finger keypress than a single index-finger keypress. Miller suggested that this complexity-based BCE-like effect has its locus in Task 1 Motor execution and its source in Task 2 central stage, similar to the no-go BCE. Thus, this phenomenon was accounted for by a model similar to that of the no-go BCE. However, it is implausible that inhibition of an already prepared response is the mechanism that causes the complexity-based BCE-like effect. Instead, it is possible that this response-complexity-based BCE-like effect was caused by motor-interference occurring when the two responses are made in close temporal succession (e.g., Ketelaars, Khan, & Franks, 1999; for evidence that this especially happens with two hand responses, see e.g., Franz, 1997; Rinkenauer, Ulrich, & Wing, 2001; Spijkers & Heuer, 1995), or that programming of the triple-response in Task 2 could have taken longer, and thus RTs were prolonged (Fischman, 1984; Sternberg, Monsell, Knoll, & Wright, 1978).

The complexity-based BCE-like effect matches the force-based BCE-like effect (Miller & Alderton, 2006) in most aspects. Miller and Alderton (2006) observed harder keypresses in Task 1 when the response required in Task 2 was a hard relative to soft keypress. Thus, for the force-based BCE-like effect it cannot be ruled out that it was at least partially enabled by the common effector system (Huestegge, Pieczykolan, & Janczyk, 2018). Nevertheless, Miller and Alderton (2006) suggested a locus in Task 1 motor execution and a source in Task 2 central stage, and thus a model in line with the one for the no-go BCE. As the mechanism causing this phenomenon, Miller and Alderton suggested that processing of Stimulus 2 "activated some internal representation associated with a high-force response" (p. 157). This assumption is in line with studies that documented the important role of effect anticipation for BCEs (see Janczyk et al., 2014; Renas et al., 2018). It is thus conceivable that the anticipation of the Response 2 force could have influenced Response 1 force.

Taken together, both motor-related BCE-like phenomena are likely to share their locus and source with the no-go BCE. The mechanisms causing both phenomena, however, appear to differ from each other and from the mechanism causing the no-go BCE. Nevertheless, up to this point it appears that the response-complexity-based BCE-like effect (Miller, 2006, Experiment 3) and the force-based BCE-like effect (Miller & Alderton, 2006) are closer related to the no-go BCE than to the compatibility-based BCEs. However, insights about aspects such as processing adjustments and working memory foundations lack, and it cannot be ruled out that dimensional overlap is a precondition in both motor-related BCE-like phenomena. Thus, future research is needed to distinguish these phenomena from the compatibility-based BCEs and to investigate how closely they are related to the no-go BCE.

7.3 Implications for theories of dual-tasking

The compatibility-based BCE, the no-go BCE, and the phenomena related to both BCEs are evidence of parallel processing in dual-tasks. However, the results from Studies 1-4 of the present dissertation suggest that models for different types of BCEs – and presumably also for BCE-like phenomena – differ qualitatively. Thus, the way in which parallel processing occurs also differs qualitatively for different types of BCEs and BCE-like phenomena. This means that each of these observations contradict the notion of a completely encapsulated bottleneck in dual tasks *in a different way*.

In the case of the compatibility-based BCEs, the stimulus-categorization model (Study 4) assumes that the capacity-limited central stage in Task 1 receives activation from Task 2. From a serial processing perspective, this suggests that the central stage is not completely encapsulated, but to some extent permeable for activation from other tasks. Even though this means that parallel processing during the central stage of Task 1 is possible to some extent, the assumption that the central stage is capacity-limited remains untouched. In other words, the capacity-limited stage is still only available for one task at a time. According to this view, one would assume that the response activation accumulated for Task 2 cannot be used to build on in Task 2 central stage. Instead, the accumulation process that needs to be completed to select the correct Response 2 starts from scratch in Task 2. If, however, a parallel processing perspective is taken, it would be assumed that central stages of both tasks run in parallel. However, as Task 1 central processing is prioritized, it receives more resources and is finished earlier than Task 2 central processing. If this were the case, the response activation for Task 2 accumulated in parallel to Task 1 central stage should at least to some degree be available the moment Task 1 has finished central processing and Task 2 gains the remaining resources.

Up to this point, the question whether response activation in Task 2 is set to zero when Task 2 central stage starts (serial perspective; for evidence, see Schubert et al., 2008) or whether it continues to accumulate under certain conditions (parallel perspective; for evidence see Thomson & Watter, 2013) remains to be answered. In order to gain insights about the Task 2 response activation level in the course of time, it could be fruitful to fit a computational model that allows for estimating parameters for two tasks at the same time to data of a compatibility-based BCE task. Such a model could for instance be created by modifying the DMC (Ulrich et al., 2015; for a similar suggestion see also Study 3, General Discussion).

The no-go BCE contradicts the notion of an encapsulated bottleneck in a different way than the compatibility-based BCE. The model for the no-go BCE (see Study 1-3) assumes that the motor stage in Task 1 receives the inhibition arising in Task 2 central stage in the case an already prepared response has to be withheld in a no-go trial. This model neither contradicts the notion of strictly serial central processing nor the idea of parallel central processing. However, it suggests that the bottleneck is *permeable* under certain circumstances and that certain byproducts of central processing can leak the bottleneck and interfere with other processes running in parallel. In the case of the no-go BCE, the inhibition needed to withhold an already prepared Response 2 leaks the capacity-limited central stage (i.e., the bottleneck) and affects Task 1 motor stage.

In a nutshell, the results of the present dissertation contradict the notion that the capacity-limited central stage of processing – also known as the bottleneck – is an encapsulated processing stage. In fact, the capacity-limited central stage even appears to be the hub of between-task interference in dual-tasking. In the case of the compatibility-based BCEs, it receives activation from Task 2 response activation, whereas in the case of the no-go BCE it passes on inhibition to the motor stage in Task 1. Although both observations are in line with the notion of parallel processing in dual-tasking in general, they can also be explained from a serial processing view. To distinguish between both theories of dual-tasking, future studies should apply computational modelling approaches to investigate the Task 2 response activation level in the course of time and specify models for other BCE-like phenomena.

8 Conclusion

The main question of the present dissertation was: Can we distinguish different types of backward crosstalk? The answer to this question is a clear yes. Studies 1-3 showed that the no-go BCE indeed differs from the compatibility-based BCEs in (1) its locus and source, (2) the mechanism it is caused by, and (3) in the way processing is adjusted based on characteristics of the previous trial. Thus, the no-go BCE and the compatibility-based BCE should be seen as two different types of backward crosstalk. Furthermore, results of Study 4 indicate that both compatibility-based BCEs, namely the S1-R2 BCE and the R1-R2 BCE, can be distinguished by the capacity-limited process they are based on. Importantly, the types of BCEs under investigation here all appear to contradict the notion of a completely encapsulated stage of central processing in dual-tasking in a *different* way. Evidence for each type of BCE rather suggests that the capacity-limited central stage of processing is actually the hub for dual-tasking interference.

9 References

Allen, P. A., Lien, M.-C., & Jardin, E. (2017). Age-related emotional bias in processing two emotionally valenced tasks. *Psychological Research, 81,* 289–308.

Bissett, P. G., Nee, D. E., & Jonides, J. (2009). Dissociating interference-control processes between memory and response. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35,* 1306–1316.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108,* 624–652.

Bowman, L. L., Levine, L. E., Waite, B. M., & Gendron, M. (2010). Can students really multitask? An experimental study of instant messaging while reading. *Computers & Education, 54,* 927–931.

Braem, S., Abrahamse, E. L., Duthoo, W., & Notebaert, W. (2014). What determines the specificity of conflict adaptation? A review, critical analysis, and proposed synthesis. *Frontiers in psychology, 5,* 1134.

Brown, J. W., Reynolds, J. R, & Braver, T. S. (2007). A computational model of fractionated conflict-control mechanisms in task-switching. *Cognitive Psychology, 55,* 37–85.

Brunia, C. H. (1983). Motor preparation: Changes in amplitude of Achilles tendon reflexes during a fixed foreperiod of one second. *Psychophysiology, 20,* 658–664.

de Jong, R. (1993). Multiple bottlenecks in overlapping task performance. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 965–980.

Donders, F. C. (1969). On the speed of mental processes. *Acta Psychologica, 30,* 412–431.

Dreisbach, G., & Haider, H. (2008). That’s what task sets are for: shielding against irrelevant information. *Psychological Research, 72,* 355-361.

Dreisbach, G., & Haider, H. (2009). How task representations guide attention: Further evidence for the shielding function of task sets. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35,* 477–486.

Durst, M., & Janczyk, M. (2018). The motor locus of no-go backward crosstalk. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 44,* 1931–1946.

Durst, M., & Janczyk, M. (2019). Two types of backward crosstalk: Sequential modulations and evidence from the diffusion model. *Acta Psychologica, 193,* 132–152.

Durst, M., Ulrich, R., & Janczyk, M. (2019). To prepare or not to prepare? When preparation of a response in Task 2 induces extra performance costs in Task 1. *Psychonomic Bulletin & Review*. Advance online publication. https://doi.org/10.3758/s13423-019-01581-1

Eder, A. B., Pfister, R., Dignath, D., Hommel, B. (2016). Anticipatory affect during action preparation: Evidence from backward compatibility in dual-task performance. *Cognition and Emotion, 31,* 1211–1224.

Egner, T. (2007). Congruency sequence effects and cognitive control. *Cognitive, Affective & Behavioral Neuroscience, 7,* 380–390.

Ellenbogen, R., & Meiran, N. (2008). Working memory involvement in dual-task performance: Evidence from the backward compatibility effect. *Memory & Cognition, 36,* 968–978.

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Attention, Perception, & Psychophysics, 16,* 143–149.

Fagot, C., & Pashler, H. (1992). Making two responses to a single object: Implications for the central attentional bottleneck. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 1058–1079.

Fischer, R., Gottschalk, C., & Dreisbach, G. (2014). Context-sensitive adjustment of cognitive control in dual-task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40,* 399–416.

Fischer, R., & Hommel, B. (2012). Deep thinking increases task-set shielding and reduces shifting flexibility in dual-task performance. *Cognition, 123,* 303–307.

Fischer, R., Miller, J., & Schubert, T. (2007). Evidence for parallel semantic memory retrieval in dual tasks. *Memory & Cognition, 35,* 1685–1699.

Fischer, R., & Plessow, F. (2015). Efficient multitasking: Parallel versus serial processing of multiple tasks. *Frontiers in Psychology, 6,* 1366.

Fischman, M. G. (1984). Programming time as a function of number of parts and changes in movement direction. *Journal of Motor Behavior, 16,* 405–423.

Franz, E. A. (1997). Spatial coupling in the coordination of complex actions. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 50,* 684–704.

Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions: A latent-variable analysis. *Journal of Experimental Psychology: General, 133,* 101–135.

Goschke, T. (2000). Intentional reconfiguration and involuntary persistence in task-set switching. In S. Monsell & J. Driver (Eds.), *Attention and performance XVIII: Control of cognitive processes* (pp. 331–355). Cambridge, MA: MIT Press.

Goschke, T. (2003). Voluntary action and cognitive control from a cognitive neuroscience perspective. In S. Maasen, W. Prinz & G. Roth (Eds.), *Voluntary action: Brains, minds, and sociality* (pp. 49–85). New York, NY: Oxford University Press.

Grabbe, J. W., & Allen, P. A. (2012). Cross-task compatibility and age-related dual-task performance. *Experimental Aging Research, 38,* 469–487.

Gratton, G., Coles, M. G., & Donchin, E. (1992). Optimizing the use of information: Strategic control of activation of responses. *Journal of Experimental Psychology: General, 121,* 480–506.

Gratton, G., Coles, M. G. H., Sirevaag, E. J., Eriksen, C. W., & Donchin, E. (1988). Pre- and poststimulus activation of response channels: A psychophysiological analysis. *Journal of Experimental Psychology: Human Perception and Performance, 14*, 331-344.

Hackley, S. A., & Miller, J. (1995). Response complexity and precue interval effects on the lateralized readiness potential. *Psychophysiology, 32,* 230–241.

Heil, M., Osman, A., Wiegelmann, J., Rolke, B., & Hennighausen, E. (2000). N200 in the Eriksen-task: Inhibitory executive process? *Journal of Psychophysiology, 14,* 218–225.

Hembrooke, H., & Gay, G. (2003). The laptop and the lecture: The effects of multitasking in learning environments. *Journal of Computing in Higher Education, 15,* 46–64.

Henry, F. M., & Rogers, D. (1960). Increased response latency for complicated movements and a ‘‘memory drum’’ theory of neuromotor reaction. *Research Quarterly, 31,* 448–458.

Herman, L. M., & Kantowitz, B. H. (1970). The psychological refractory period effect: Only half the double stimulation story? *Psychological Bulletin, 73,* 74–88.

Hibberd, D. L., Jamson, S. L., & Carsten, O. M. J. (2013). Mitigating the effects of in-vehicle distractions through use of the psychological refractory period paradigm. *Accident Analysis & Prevention,* 50, 1096–1103.

Hommel, B. (1998). Automatic stimulus–response translation in dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 1368–1384.

Hommel, B., & Eglau, B. (2002). Control of stimulus-response translation in dual-task performance. *Psychological Research, 66,* 260–273.

Hommel, B., Müsseler, J., Aschersleben, G., Prinz, W. (2001). The Theory of Event Coding (TEC): A framework for perception and action planning. *Behavioral and brain sciences, 24,* 849–937.

Hübner, R., & Lehle, C. (2007). Strategies of flanker coprocessing in single and dual tasks. *Journal of Experimental Psychology: Human Perception and Performance, 33,* 103–123.

Huestegge, L., Pieczykolan, A., & Janczyk, M. (2018). Backward crosstalk and the role of dimensional overlap within and between tasks. *Acta Psychologica, 188,* 139–147.

Janczyk, M. (2016). Sequential modulation of backward crosstalk and task-shielding in dual-tasking. *Journal of Experimental Psychology: Human Perception and Performance, 42,* 631–647.

Janczyk, M., & Huestegge, L. (2017). Effects of a no-go Task 2 on Task 1 performance in dual-tasking: From benefits to costs. *Attention, Perception, & Psychophysics, 79,* 796–806.

Janczyk, M., & Leuthold, H. (2018). Effector system-specific sequential modulations of congruency effects. *Psychonomic Bulletin & Review, 25,* 1066–1072.

Janczyk, M., Pfister, R., Hommel, B., & Kunde, W. (2014). Who is talking in backward crosstalk? Disentangling response-from goal-conflict in dual-task performance. *Cognition, 132,* 30–43.

Janczyk, M., Pfister, R., Wallmeier, G., & Kunde, W. (2014). Exceptions to the PRP effect? A comparison of prepared and unconditioned reflexes. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*, 776–786.

Janczyk, M., Renas, S., & Durst, M. (2018). Identifying the locus of compatibility-based backward crosstalk: Evidence from an extended PRP paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 44,* 261–276.

Janczyk, M., Mittelstädt, P., & Wienrich, C. (2018). Parallel dual-task processing and task-shielding in older and younger adults: Behavioral and diffusion model results. *Experimental Aging Research, 44,* 95–116.

Janczyk, M., Nolden, S., & Jolicoeur, P. (2015). No differences in dual-task costs between forced- and free-choice tasks. *Psychological Research, 79,* 463–477.

Johnston, J. C., & McCann, R. S. (2006). On the locus of dual-task interference: Is there a bottleneck at the stimulus classification stage? *The Quarterly Journal of Experimental Psychology, 59,* 694–719.

Karlin, L. & Kestenbaum, R. (1968). Effects of numbers of alternatives on the psychological refractory period. *Quarterly Journal of Experimental Psychology, 20,* 167–178.

Ketelaars, M. A., Khan, M. A., & Franks, I. M. (1999). Dual-task interference as an indicator of online programming in simple movement sequences. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 1302–1315.

Kiesel, A., Wendt, M., & Peters, A (2007). Task switching: On the origins of response congruency effects. *Psychological Research, 71,* 117–125.

Ko, Y.-T., & Miller, J. (2014). Locus of backward crosstalk effects on task 1 in a psychological refractory period task. *Experimental Psychology, 61,* 30–37.

Koch, I., Poljac, E., Müller, H., & Kiesel, A. (2018). Cognitive structure, flexibility, and plasticity in human multitasking—An integrative review of dual-task and task-switching research. *Psychological Bulletin, 144,* 557–583.

Koch, I., & Prinz, W. (2002). Process interference and code overlap in dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 192–201.

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility—A model and taxonomy. *Psychological Review, 97,* 253–270.

Kühn, S., Elsner, B., Prinz, W., & Brass, M. (2009). Busy doing nothing: Evidence for nonaction—effect binding. *Psychonomic Bulletin & Review, 16,* 542–549.

Lehle, C., & Hübner, R. (2009). Strategic capacity sharing between two tasks: Evidence from tasks with the same and with different task sets. *Psychological Research, 73,* 707–726.

Levy, J., & Pashler, H. (2008). Task prioritisation in multitasking during driving: Opportunity to abort a concurrent task does not insulate braking responses from dual-task slowing. *Applied Cognitive Psychology*, 22, 507–525.

Lien, M.-C., & Proctor, R. W. (2000). Multiple spatial correspondence effects on dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 1260–1280.

Lien, M.-C., & Proctor, R. W. (2002). Stimulus-response compatibility and psychological refractory period effects: Implications for response selection. *Psychonomic Bulletin & Review, 9,* 212–238.

Lien, M.-C., Ruthruff, E., Hsieh, S.-L., & Yu, Y.-T. (2007). Parallel central processing between tasks: Evidence from lateralized readiness potentials. *Psychonomic Bulletin & Review, 14,* 133–141.

Logan, G. D., & Delheimer, J. A. (2001). Parallel memory retrieval in dual-task situations: II. Episodic memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27,* 668–685.

Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review, 108,* 393–434.

Logan, G. D., & Schulkind, M. D. (2000). Parallel memory retrieval in dual-task situations: I. Semantic memory. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 1072–1090.

McCann, R. S., & Johnston, J. C. (1992). Locus of the single-channel bottleneck in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance 18,* 471–484.

Meiran, N. (1996). Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22,* 1423–1442.

Meyer, D. E., & Kieras, D. E. (1997). A computational theory of executive cognitive processes and multiple-task performance: 2. Accounts of psychological refractory-period phenomena. *Psychological Review, 104,* 749–791.

Miller, J. (2006). Backward crosstalk effects in psychological refractory period paradigms: Effects of second-task response types on first-task response latencies. *Psychological Research, 70,* 484–493.

Miller, J. (2017). Psychophysiological measurement of backward response activation in the prioritized processing paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 43,* 941–953.

Miller, J., & Alderton, M. (2006). Backward response-level crosstalk in the psychological refractory period paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 32,* 149–165.

Miller, J., & Durst, M. (2014). “Just do it when you get a chance”: The effects of a background task on primary task performance. *Attention, Perception, & Psychophysics, 76,* 2560–2574.

Miller, J., & Durst, M. (2015). A comparison of the psychological refractory period and prioritized processing paradigms: Can the response-selection bottleneck model explain them both? *Journal of Experimental Psychology: Human Perception and Performance, 41,* 1420–1441.

Miller, J., Ulrich, R., & Rolke, B. (2009). On the optimality of serial and parallel processing in the psychological refractory period paradigm: Effects of the distribution of stimulus onset asynchronies. *Cognitive Psychology, 58,* 273–310.

Mittelstädt, V., & Miller, J. (2017). Separating limits on preparation versus online processing in multitasking paradigms: Evidence for resource models. *Journal of Experimental Psychology: Human Perception and Performance, 43,* 89–102.

Navon, D., & Miller, J. (1987). Role of outcome conflict in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance,* 13, 435–448.

Navon, D., & Miller, J. (2002). Queuing or sharing? A critical evaluation of the single-bottleneck notion. *Cognitive Psychology, 44,* 193–251.

Oriet, C., Tombu, M., & Jolicoeur, P. (2005). Symbolic distance affects two processing loci in the number comparison task. *Memory & Cognition, 33,* 913–926.

Paelecke, M., & Kunde, W. (2007). Action-effect codes in and before the central bottleneck: Evidence from the psychological refractory period paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 33,* 627–644.

Paridon, H. M., & Kaufmann, M. (2010). Multitasking in work-related situations and its relevance for occupational health and safety: Effects on performance, subjective strain and physiological parameters. *Europe's Journal of Psychology, 6,* 110–124.

Pashler, H. (1984). Processing stages in overlapping tasks: Evidence for a central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 358–377.

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin, 116,* 220–244.

Plessow, F., Schade, S., Kirschbaum, C., & Fischer, R. (2012). Better not to deal with two tasks at the same time when stressed? Acute psychosocial stress reduces task shielding in dual-task performance. *Cognitive, Affective, & Behavioral Neuroscience, 12,* 557–570.

Praamstra, P., Kleine, B. U., & Schnitzler, A. (1999). Magnetic stimulation of the dorsal premotor cortex modulates the Simon effect. *Neuroreport, 10,* 3671–3674.

Ratcliff, R. (1978). A theory of memory retrieval. *Psychological Review, 85,* 59–108.

Renas, S., Durst, M., & Janczyk, M. (2018). Action effect features, but not anatomical features, determine the backward crosstalk effect: Evidence from crossed-hands experiments. *Psychological Research, 82,* 970–980.

Rinkenauer, G., Ulrich, R., & Wing, A. M. (2001). Brief bimanual force pulses: Correlations between the hands in force and time. *Journal of Experimental Psychology: Human Perception and Performance, 27,* 1485–1497.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General*, *124,* 207–231.

Rosenbaum, D. A., Weber, R. J., Hazelett, W. M., & Hindorff, V. (1986). The parameter remapping effect in human performance: Evidence from tongue twisters and finger fumblers. *Journal of Memory and Language, 25,* 710–725.

Röttger, E., & Haider, H. (2017). Investigating the characteristics of “not responding”: Backward crosstalk in the PRP paradigm with forced vs. free no-go decisions. *Psychological Research, 81,* 596–610.

Ruiz Fernández, S., & Ulrich, R. (2010). Late backward effects in the refractory period paradigm: effects of Task 2 execution on Task 1 performance. *Psychological Research, 74,* 378–387.

Ruthruff, E., Johnston, J. C., & Remington, R. W. (2009). How strategic is the central bottleneck: Can it be overcome by trying harder? *Journal of Experimental Psychology: Human Perception and Performance, 35,* 1368–1384.

Ruthruff, E., Pashler, H., & Klaasen, A. (2001). Processing bottlenecks in dual-task performance: Structural limitation or strategic postponement? *Psychonomic Bulletin & Review, 8,* 73–80.

Sasaki, K., Gemba, H., Nambu, A., & Matsuzaki, R. (1993). No-go activity in the frontal association cortex of human subjects. *Neuroscience Research, 18,* 249–252.

Scherbaum, S., Gottschalk, C., Dshemuchadse, M., & Fischer, R. (2015). Action dynamics in multitasking: The impact of additional task factors on the execution of the prioritized motor movement. *Frontiers in Psychology, 6,* 934.

Schuch, S., Dignath, D., Steinhauser, M., & Janczyk, M. (2018). Monitoring and control in multitasking. *Psychonomic Bulletin & Review, 26,* 222–240.

Schubert, T., Fischer, R., & Stelzel, C. (2008). Response activation igrattonn overlapping tasks and the response-selection bottleneck. *Journal of Experimental Psychology: Human Perception and Performance, 34,* 376–397.

Schweickert, R. (1978). A critical path generalization of the additive factor method: Analysis of a stroop task. *Journal of Mathematical Psychology, 18,* 105–139.

Simon, J. R., & Rudell, A. P. (1967). Auditory S-R compatibility: The effect of an irrelevant cue on information processing. *Journal of Applied Psychology, 51,* 300–304.

Smith, M. C. (1969). The effect of varying information on the psychological refractory period. *Acta Psychologica, 30,* 220–231.

Telford, C. W. (1931). The refractory phase of voluntary and associative responses. *Journal of Experimental Psychology, 14,* 1–36.

Tombu, M., & Jolicœur, P. (2004). Virtually no evidence for virtually perfect time-sharing. *Journal of Experimental Psychology: Human Perception and Performance, 30,* 795–810.

Spijkers, W. A. C., & Heuer, H. (1995). Structural constraints on the performance of symmetrical bimanual movements with different amplitudes. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 48*, 716–740.

Stelzel, C., Brandt, S. A., & Schubert, T. (2009). Neural mechanisms of concurrent stimulus processing in dual tasks. *NeuroImage, 48,* 237–248.

Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. *Acta Psychologica, 30,* 276–315.

Sternberg, S., Monsell, S., Knoll, R. L., & Wright, C. E. (1978). The latency and duration of rapid movement sequences: Comparisons of speech and typewriting. In G. E. Stelmach

(Ed.), *Information processing in motor control and learning* (pp. 117–152). New York, NY: Academic Press.

Stief, V., Leuthold, H., Miller, J., Sommer, W., & Ulrich, R. (1998). The effect of response complexity on the lateralized readiness potential. *Zeitschrift für Psychologie, 206,* 305–319.

Strayer, D. L., & Drews, F. A. (2004). Profiles in driver distraction: Effects of cell phone conversations on younger and older drivers. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *46*, 640–649.

Strayer, D. L., & Drews, F. A. (2007). Cell-phone–induced driver distraction. *Current Directions in Psychological Science, 16*, 128–131.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18,* 643–662.

Strobach, T., Liepelt, R., Pashler, H., Frensch, P. A., & Schubert, T. (2013). Effects of extensive dual-task practice on processing stages in simultaneous choice tasks. *Perception & Psychophysics, 75,* 900–920.

Stürmer, B., Leuthold, H., Soetens, E., Schröter, H., & Sommer, W. (2002). Control over location-based response activation in the Simon task: Behavioral and electrophysiological evidence. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 1345–1363.

Stürmer, B., & Leuthold, H. (2003). Control over response priming in visuomotor processing: A lateralized event-related potential study. *Experimental Brain Research, 153,* 35–44.

Thomson, S. J., Danis, L. K., & Watter, S. (2015). PRP training shows Task1 response selection is the locus of the backward response compatibility effect. *Psychonomic Bulletin & Review, 22,* 212–218.

Thomson, S. J., & Watter, S. (2013). Information continuity across the response selection bottleneck: Early parallel Task 2 response activation contributes to overt Task 2 performance. *Attention, Perception, & Psychophysics, 75,* 934–953.

Thomson, S. J., Watter, S., & Finkelshtein, A. (2010). Parallel response selection in dual-task situations via automatic category-to-response translation. *Attention, Perception, & Psychophysics, 72,* 1791–1802.

Tombu, M., & Jolicœur, P. (2003). A central capacity sharing model of dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 3–18.

Ulrich, R., Schröter, H., Leuthold, H., & Birngruber, T. (2015). Automatic and controlled stimulus processing in conflict tasks: Superimposed diffusion processes and delta functions. *Cognitive Psychology, 78,* 148–174.

Van Selst, M., & Johnston, J. C. (1997). Dual-task interference when a response is not required. In M. G. Shafto & P. Langley (Eds.), *Proceedings of the nineteenth annual conference of the Cognitive Science Society* (pp. 787–792). Mahwah, NJ: Erlbaum.

Verbruggen, F., & Logan, G. D. (2008). Automatic and controlled response inhibition: Associative learning in the go/no-go and stop-signal paradigms. *Journal of Experimental Psychology: General, 137,* 649–672.

Watter, S., & Logan, G. D. (2006). Parallel response selection in dual-task situations. *Perception & Psychophysics, 68,* 254–277.

Welford, A. T. (1952). The ‘psychological refractory period’ and the timing of high-speed performance—a review and a theory. *British Journal of Psychology. General Section, 43,* 2–19.

Wood, E., Zivcakova, L., Gentile, P., Archer, K., De Pasquale, D., & Nosko, A. (2012). Examining the impact of off-task multi-tasking with technology on real-time classroom learning. *Computers & Education, 58,* 365–374.

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10 Appendix

10.1 Study 1

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The Motor Locus of No-Go Backward Crosstalk

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A frequent observation in dual-task studies is the backward crosstalk effect (BCE), meaning that aspects of a secondary Task 2 influence Task 1 performance. Up to this point, 2 major types of the BCE were investigated: a BCE based on dimensional overlap between both stimuli and/or responses (the compatibility-based BCE), and a BCE based on whether Task 2 is a go or no-go task (the no-go BCE). Recent evidence suggests that the compatibility-based BCE has its locus inside the response selection stage. The available evidence for the locus of the *no-go BCE* is still mixed, however. To this end, the 3 experiments reported in the present study used an extended psychological refractory period (PRP) paradigm with 3 subsequent tasks. Applying the locus of slack logic in Experiment 1, the no-go BCE was not absorbed into the cognitive slack and, thus, a locus before response selection could be ruled out. Subsequently applying the effect propagation logic in Experiment 2 and 3, the no-go BCE arising in Task 1 was even *inverted* in Task 3. Because no propagation of the no-go BCE was observed, a locus before or in response selection could be ruled out. Thus, we conclude that the no-go BCE has its locus during motor execution. Because the no-go BCE and the compatibility-based BCE are located in different stages, we suggest that both types of the BCE do not share a common underlying mechanism.

Keywords: PRP, locus of slack, dual-task, backward crosstalk, go/no-go

Human dual-task performance has been extensively studied in the psychological refractory period (PRP) paradigm (Pashler, 1994; Welford, 1952). In the PRP paradigm usually two tasks are performed in rapid succession, that is, participants on each trial first carry out Response 1 (R1) to Stimulus 1 (S1) and then Response 2 (R2) to Stimulus 2 (S2). The crucial manipulation is the stimulus onset asynchrony (SOA), that is, the interval between onset of S1 and S2 and consequently the temporal overlap between Task 1 (T1) and Task 2 (T2). While response times for T1 (RT1) are largely unaffected by the SOA, those for T2 (RT2) increase severely the shorter the SOA—the PRP effect (Pashler, 1994; Telford, 1931) evidencing performance costs for T2 (for possible exceptions, see Janczyk, Pfister, Wallmeier, & Kunde, 2014).

A popular model explaining the PRP effect is the so called response selection bottleneck model (RSB; Pashler, 1984), which assumes that each task is processed in the three subsequent stages of perception, response selection, and motor execution. The perception and motor execution stages are supposed to be capacity-unlimited. In contrast, the response selection (RS) stage is conceived as capacity-limited, which means it can only process one task at a time (see Figure 1a) and is described as a (structural) bottleneck in human cognition. It follows that RS in T2 cannot start until RS in T1 has finished and, thus, RT2s get prolonged at a short SOA: When T2 cannot gain direct access to the RS stage, it simply waits, and this idle time is called cognitive slack.

However, converging evidence for simultaneous processing of more than one task at a time was accumulated in the last decades (e.g., Hazeltine, Teague, & Ivry, 2002; Miller, Ulrich, & Rolke, 2009; Mittelstädt & Miller, 2017). One particular effect that contradicts a strict bottleneck explanation in dual-tasking is that features of T2 can already influence performance in T1. Such effects have been termed *backward crosstalk effects* (BCEs). Studies beginning with Hommel (1998) reported BCEs based on dimensional overlap and, thus, compatibility of features (stimuli, responses; Ellenbogen & Meiran, 2008; Janczyk, Pfister, Hommel, & Kunde, 2014; Lien & Proctor, 2000; Schubert, Fischer, & Stelzel, 2008; Watter & Logan, 2006), but Miller (2006) reported cases even without such dimensional overlap. Specifically, in Experiment 1 and 2, he observed that the performance in T1 was also influenced by whether T2 was a go or a no-go task. It is of debate whether both variants are akin or represent (qualitatively) different kinds of BCEs. If both kinds of BCEs were indeed akin they should have the same locus (i.e., both BCEs arise in the same processing stage of T1) and the same source (i.e., both BCEs are caused by the same processing stage of T2).

The Locus of the Compatibility-Based BCE

In a typical experiment investigating the compatibility-based BCE (Hommel, 1998), participants are presented with colored letters and are instructed to respond to the color of the letter with a left versus right manual keypress and to the identity of the letter

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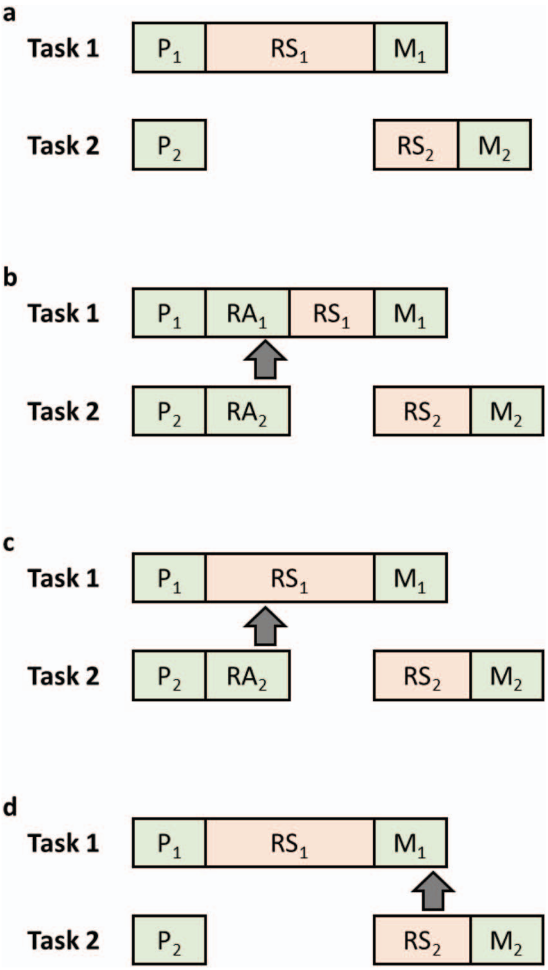

Figure 1. (a) Illustration of the original response selection bottleneck (RSB) model (e.g., Pashler, 1994). Task 2 response selection (RS) can only start when Task 1 RS is finished. No (backward) crosstalk can occur in this model. (b) Illustration of a modified RSB model (Hommel, 1998; Lien & Proctor, 2002). A parallel stage of response activation (RA) starts after stimulus identification. (Backward) crosstalk is enabled when both RA stages overlap temporally (as is illustrated by the gray arrows). (c) Illustration of a model according to which RA occurs automatically if RS cannot start immediately in Task 2. (Backward) crosstalk arises if Task 2 RA feeds directly into Task 1 RS (Janczyk, Renas, & Durst, 2017, Figure 1; Thomson et al., 2015, Figure 1). (d) Illustration of a model where (backward) crosstalk arises from temporally overlapping Task 2 RS and Task 1 motor stage (Janczyk & Huestegge, 2017; Miller, 2006, see general discussion for a tentative suggestion). (P = perceptual stage; RS = response selection; RA = response activation; M = motor stage, the subscript indicates Task 1 and 2, respectively). See the online article for the color version of this figure.

with a vocal “left” versus “right” utterance or pedal key press. When R1 and R2 are spatially compatible (e.g., a left keypress in R1 and a vocal “left” utterance or a right keypress in R1 and a vocal “right” utterance), RT1s are shorter compared with incompatible responses.

Such results imply that some RS-related aspects of T2 must have run in parallel to T1 RS to some extent, which is in contrast to the classic RSB model. To account for this, Hommel (1998) suggested to subdivide the RS stage into two sequential substages, (a) the response activation stage (RA) dealing with automatic and capacity-unlimited stimulus-response (S-R) translation, and (b) the capacity-limited RS that “deals with the outcome of all the translations, hence, the resulting response-activation pattern” (p. 1381; see Figure 1b, see also Lien & Proctor, 2002).[1] Because RA can run in parallel with other stages, crosstalk occurs if T1 and T2 RA overlap in time. If then T1 RA is the locus of this BCE (i.e., the stage in T1 that is affected), T1 RA should be *prolonged* in incompatible relative to compatible trials, yielding a BCE in RTs. Accordingly, then T2 RA is the stage that causes this BCE in T1 RA and, thus, the *source* of this BCE.

In contrast, Thomson, Danis, and Watter (2015) assumed that an (automatic) RA occurs after the perceptual stage of T2 because T2 does not gain direct access to the bottleneck stage of RS. This T2 RA could then interfere with T1 RS (see Figure 1c) and this was tested in a training study. Because dual-task training mainly shortens the duration of RS (Strobach, Liepelt, Pashler, Frensch, & Schubert, 2013) the authors assumed that a shortening of T1 RS should reduce the opportunity for a BCE to arise between T2 RA and T1 RS. In line with this, Thomson et al. observed that the BCE indeed became smaller with training. The model suggested by Thomson et al. received recent support from a study by Janczyk et al. (2017) that introduced a triple-task logic (similar to what we use in the present study) to localize the compatibility-based BCE. In Experiments 1–3 of this study, a variant of the locus of slack logic (Schweickert, 1978)[2] was used and the results excluded a locus before the bottleneck stage (i.e., the perceptual or the RA stage). In two additional experiments (Experiments 4 and 5), two different approaches were taken to exclude a motor contribution to the compatibility-based BCE. For example, in Experiment 5 a stimulus/go-signal interval was introduced, and the compatibility-based BCE was eliminated when participants were provided sufficient time to prepare their responses. In summary, Janczyk et al. also concluded that the locus of the BCE is in the RS stage of T1, and suggested that it is caused by interference from (automatic) RA in T2 running in parallel to T1 RS (see Figure 1c).

In a nutshell, recently converging evidence for a RS locus of the compatibility-based BCE was accumulated in behavioral (Janczyk et al., 2017; Thomson et al., 2015) as well as LRP data (Miller, 2017).

The Locus of the No-Go BCE

Miller (2006) investigated whether BCEs exclusively occur with dimensional overlap between both tasks (Kornblum, Hasbroucq, & Osman, 1990). In Experiments 1 and 2, a manual choice-response T1 was combined with a go/no-go T2 (see Donders, 1969). Thus, in go-trials participants responded with a keypress of their right index finger and withheld this response in no-go trials. Miller observed that RT1 was prolonged when T2 was a no-go compared with go trial. We will refer to this effect as the *no-go BCE* (see

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[1] The interpretation of the RA and RS stages as being sequential processing stages may not be uncontroversial, yet it is widely received in this way in the respective literature (see Janczyk et al., 2017, for details; see also, e.g., Paelecke & Kunde, 2007; Schubert et al., 2008).

[2] This approach is explained in more detail in the Introduction to Experiment 1 that makes use of that logic as well.

Janczyk & Huestegge, 2017). The no-go BCE was replicated with a pedal go/no-go T2 in a study by Ko and Miller (2014) and it was also observed in an alternative dual-task paradigm, the *prioritized processing* (PP) paradigm (Miller & Durst, 2014, 2015).

The exact reason for the no-go BCE, however, is still debated. One line of argument suggests that the no-go BCE is caused by active inhibition (Janczyk & Huestegge, 2017; Miller, 2006) resulting from the attempt to inhibit and prevent the execution of an already prepared response in T2 (see Brunia, 1983; Heil, Osman, Wiegelmann, Rolke, & Hennighausen, 2000; Sasaki, Gemba, Nambu, & Matsuzaki, 1993). This inhibition spreads to T1 and prolongs RT1 (Miller, 2006; Miller & Durst, 2014, 2015), by inhibiting the according motor execution, as was suggested in the discussion of Ko and Miller (2014). In particular, the no-go BCE could result from a "rather general crosstalk between response selection and/or execution processes of the two tasks" (Miller, 2006, p. 492). Following this reasoning, the extent of inhibition required in a no-go trial should increase with the degree of preparation for the according R2. In line with this, Janczyk and Huestegge only observed a no-go BCE when T2 was very easy to prepare (when T2 was a simple go/no-go task).[3] In summary, it seems reasonable to assume that the no-go BCE results from a lengthened T1 motor stage in case of T2 no-go trials.

As an alternative, it was recently proposed to explain the no-go BCE in a similar vein as the compatibility-based BCE, namely by means of automatic response feature activation (Röttger & Haider, 2017). These authors compared the no-go BCE of blocks with a classic go/no-go T2 (forced-choice) to blocks where participants could freely choose whether to respond or to withhold their response to T2 (free-choice). They obtained a no-go BCE only in the forced-choice condition and, thus, reasoned that the no-go BCE is not based on inhibition but rather on automatic response feature activation (that cannot happen in free-choice tasks). Such automatically activated response features could for instance be response effects, which play a role for the selection of no-go responses (Kühn, Elsner, Prinz, & Brass, 2009) and also for the compatibility-based BCE (Janczyk, Pfister, Hommel, et al., 2014; Renas, Durst, & Janczyk, 2017).[4] In addition, compatibility may exist on a higher level in the sense that the "go representation" of T1 conflicts with the "no-go representation" of T2. In any case, the perception of a no-go S2 should automatically impair T1 performance (i.e., via T2 RA running in parallel to T1 RA or RS), because of the incompatibility with the response effect of a go R1 (e.g., the tactile effect of pressing a key) or because of the incompatibility between the abstract "go and no-go representations". In summary, according to these ideas, the no-go BCE results from the T1 RA stage (or the RS stage, against the background of the Janczyk et al., 2017; Thomson et al., 2015, studies).

The Present Study

In the present study, we investigated whether the no-go BCE is based on (a) similar cognitive mechanisms as the compatibility-based BCE or (b) rather has its locus in the later motor stage, perhaps because of T2 inhibition spilling over to T1. To this end, we conducted three PRP-like experiments with three subsequent tasks (see also Janczyk et al., 2017). Experiment 1 was designed to distinguish whether the no-go BCE is located (a) before or (b) at or after the bottleneck. This experiment ruled out a locus before the bottleneck and, thus, a locus in RA as suggested by Röttger and Haider (2017) seems unlikely. Still, as in the case of the compatibility-based BCE, the source may be in the RS stage (as was already suggested by Ko & Miller, 2014) and, thus, nonetheless both BCEs would share commonalities.

Thus, Experiment 2 and 3 were run to distinguish between (a) a locus before or during the bottleneck or (b) after the bottleneck. Combined with the results from Experiment 1, this allows to distinguish between a locus in RS or motor execution: A locus inside RS would still be in line with the idea that the no-go BCE has essentially the same cause as the compatibility based BCE (i.e., RA of T2; Röttger & Haider, 2017). A locus within the motor stage would rather fit with the ideas of inhibition spilling over from T2 (Janczyk & Huestegge, 2017; Miller, 2006) and suggest that both types of the BCE may be of distinct nature. To anticipate, results from Experiments 1–3 suggest that the no-go BCE is indeed located in motor execution.

Experiment 1

Experiment 1 applied the *locus of slack logic* (Schweickert, 1978; see Janczyk, 2013, 2017; Miller & Reynolds, 2003, for applications) to distinguish whether the no-go BCE is located (a) before or (b) at or after the bottleneck. To this end, three subsequent tasks were presented in a PRP-like manner. In each trial S1 arrived first and after a variable SOA, S2 and S3 were presented simultaneously. While T1 (the tone task) and T2 (the identity task) were two choice-tasks, T3 (the color task) was a go/no-go task. Thus, a no-go BCE was expected in T2. At a long SOA, without cognitive slack, T2 does not have to wait to gain access to RS and the no-go BCE should be observable as a prolongation of RT2. This is because the prolongation of any T2 stage caused by the no-go BCE would affect RT2 equally. At a short SOA, however, there is cognitive slack. Thus, a prolongation of any stage of T2 *before* the bottleneck (perception and RA) simply extends into the cognitive slack—the no-go BCE is *absorbed into slack*. In this case RT2s are not prolonged because the subsequent RS of T2 is not further delayed (see Figure 2). This pattern would manifest in an *underadditive interaction* of trial type (go vs. no-go) with SOA and indicates a locus of the no-go BCE before the bottleneck. However, an *additive combination* of trial type and SOA would indicate that the no-go BCE is still observed at a short SOA, and was not absorbed into slack. Then, a locus of the no-go BCE at or after the bottleneck is indicated.

Method

Participants. Twenty-four students (19 women) from the University of Tübingen, aged 18 to 27 years (M = 20.1 years,

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[3] The inhibition that is assumed to arise in no-go tasks has often been equated with the inhibition that is thought to arise in stop trials of the stop-signal paradigm (Friedman & Miyake, 2004), and the inhibition in both paradigms actually seems to arise in the same processing stage (Bissett, Nee, & Jonides, 2009). However, there is also evidence suggesting that inhibition arises automatically in the go/no-go paradigm, whereas it arises in a controlled manner in the stop-signal paradigm (Verbruggen & Logan, 2008). Taken together, evidence for the equity of no-go and stop-signal tasks is mixed and we do not wish to intermingle both paradigms at this point.

[4] According to Verbruggen and Logan (2008) such response features may also be task rules, inhibitory tags, inhibitory states, action plans, or task goals.

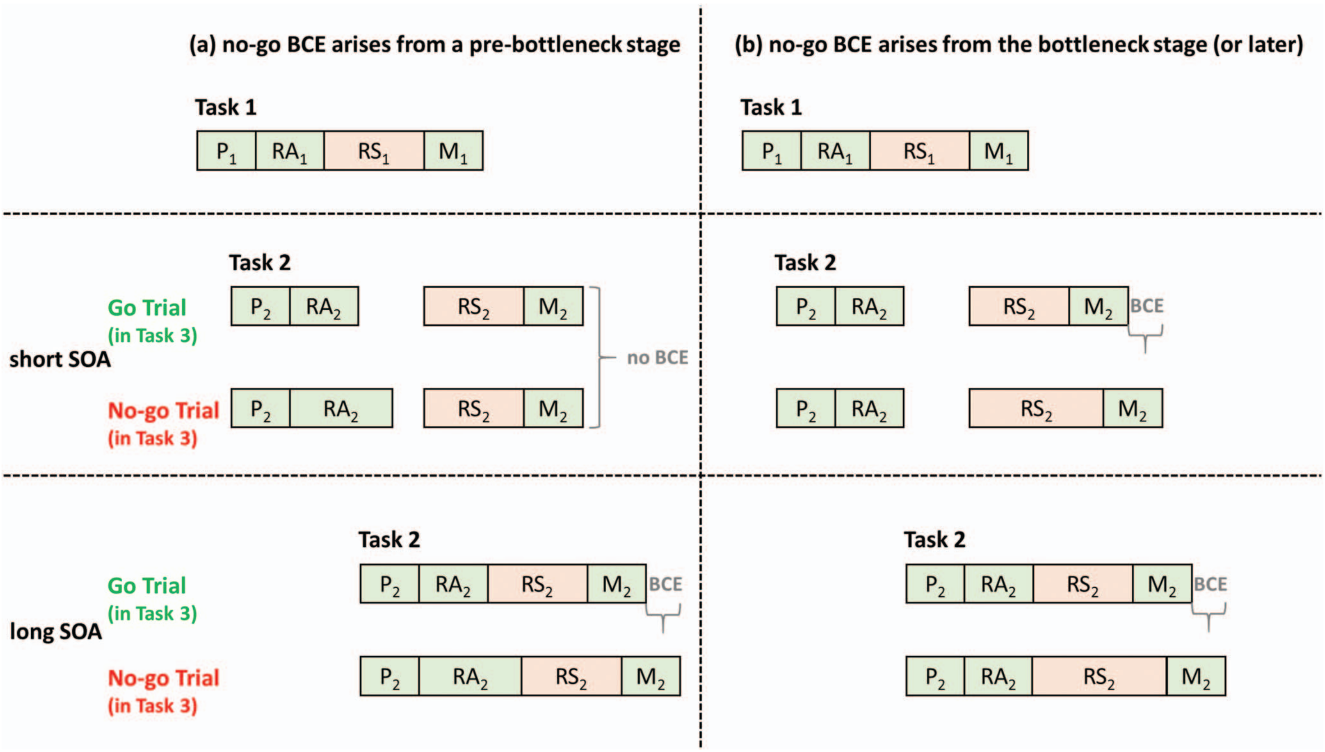

Figure 2. Illustration of the extended PRP paradigm applying the locus of slack logic (see Janczyk et al., 2017). Panel (a) illustrates the case when the no-go backward crosstalk effect (BCE) arises because of a lengthened RA stage (in Task 2), and Panel (b) illustrates the case when the BCE arises because of a lengthened RS stage (in Task 2; the predictions for a lengthened motor stage are the same). (P = perceptual stage; RS = response selection; RA = response activation; M = motor stage, the subscript indicates Task 1 and 2, respectively; Task 3 has been omitted in this illustration; the effect size of the BCE is indicated by the gray curly brackets). See the online article for the color version of this figure.

SD = 2.0), participated for monetary compensation (8€) or course credit. All participants provided written informed consent before the experiment and had normal or corrected-to-normal vision.

Apparatus and stimuli. A standard PC was used for stimulus presentation and response collection. Stimuli and instructions were presented on a 17-in. CRT monitor. For an illustration of the following, see Figure 3a and 3b. S1 was a 300 or 900 Hz tone played via headphones (50 ms). The letters ‘H’ or ‘X’ colored in blue or yellow were presented in the center of an otherwise black screen. The identity of the letter served as S2 and the color of the letter served as S3. Responses to S1 (R1) were collected with a voice key, and the experimenter coded the response identity immediately to allow for error feedback. The experimenter was in the same room, but not visible for the participant. Responses to the identity of the letter (R2) were given via manual keypresses of two response keys located to the left of the participant. Responses to the color of the letter were given via a keypress of a single response key located to the right of the participant (R3).

Task and procedure. T1 was to respond to S1 by giving a vocal R1 (“tipp” vs. “topp”). T2 was to respond to S2 with the left middle or index finger. T3 was a go/no-go response to S3 with the right index finger.

Every trial started with a white fixation cross (250 ms), followed by a blank screen (250 ms), and the onset of S1. After a variable SOA of 50 versus 1,000 ms (similar to the study by Janczyk et al., 2017), the colored letter (S2/S3) was presented, until R2 and R3 were registered. The next trial started after an intertrial interval (ITI) of 1,000 ms. In case of wrong responses or general errors (no response within 4,000 ms following S2/S3 onset, responses in the wrong order, and so on), specific error feedback was provided for 1,000 ms before the ITI.

Participants first performed a short practice block of 10 randomly drawn trials, which was followed by 10 experimental blocks of 64 trials each, resulting from four repetitions of all combinations of 2 S1 × 2 S2 × 2 S3 × 2 SOAs. All trials were presented in a random order. Participants received written instructions that emphasized speed and accuracy, and were asked to give R1, R2, and R3 successively in fixed order. The S-R mapping of all tasks was counterbalanced across participants.

Design and analysis. A trial was considered a go trial when R3 was to be given. Otherwise, it was considered a no-go trial. Data from the first two blocks were considered practice and were excluded from analyses, as were trials with general errors. For the analysis of response times (RTs), only entirely correct trials were included. Further, no-go trials were excluded from RT3 analysis and trials with RTs deviating more than 2.5 *SD*s from the individual cell mean were considered outliers and were excluded from all RT analyses. Concerning T1 and T2, mean correct RTs and error rates (ERs) were

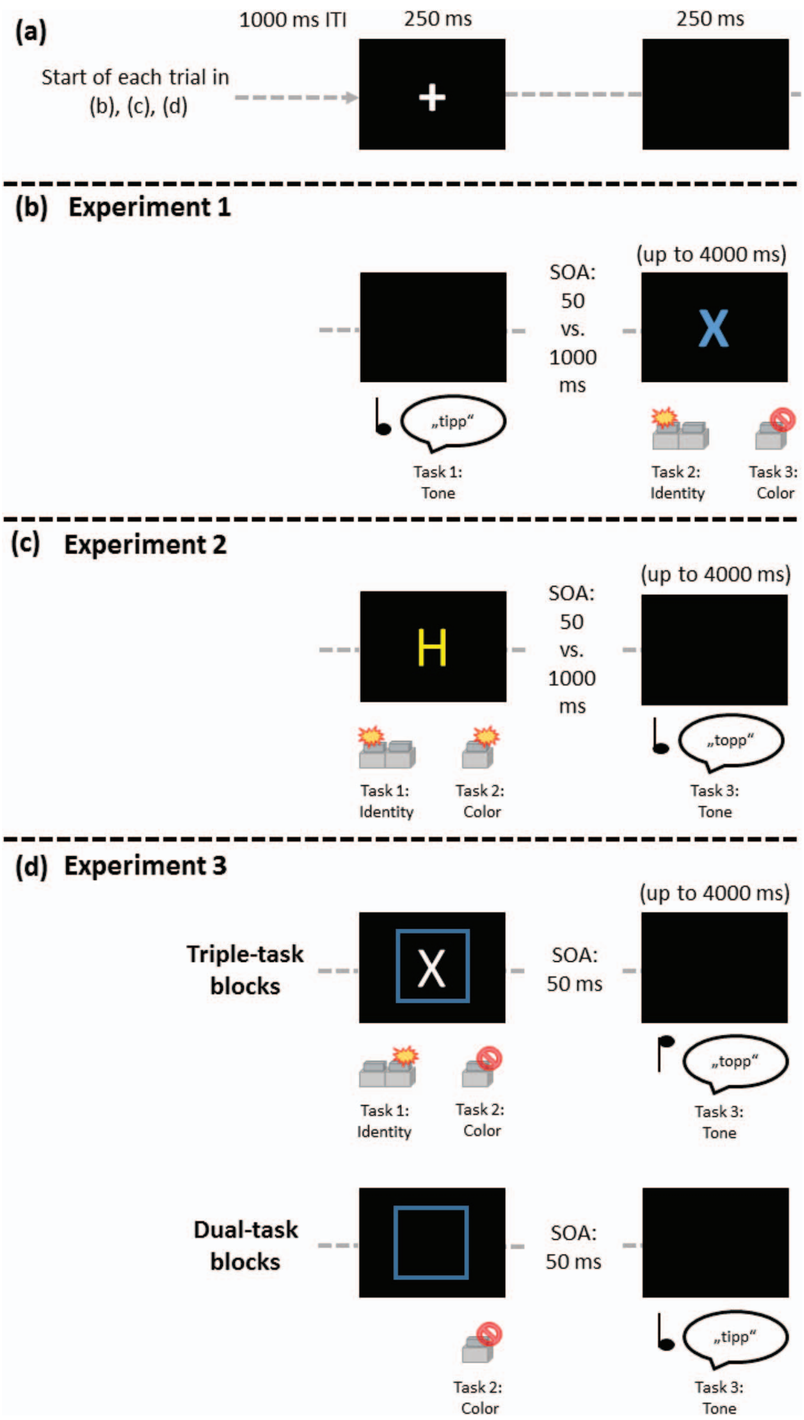

Figure 3. Illustration of the trial structure for each experiment of the present study. (a) Every trial (in Experiments 1–3) started with a 1,000 ms intertrial interval (ITI), which was followed by a fixation cross lasting for 250 ms and a blank screen lasting for 250 ms. Note, that each trial lasted for a maximum of 4,000 ms plus the SOA duration of the according trial or until all responses were given. The tone always lasted for 50 ms, while the letter and color stimuli remained on screen until the trial had ended. The tone task always was a two-choice task requiring a vocal utterance ("tipp" vs. "topp"), the identity task was a two-choice task (left index vs. left middle finger), and the color task was a go/no-go task (give vs. withhold a response with the right index finger). (b) Trial structure for Experiment 1. (c) Trial structure for Experiment 2. (d) Trial structure for Experiment 3. See the online article for the color version of this figure.

submitted to 2×2 analyses of variance (ANOVA) with SOA (50 vs. 1,000 ms) and trial type (go vs. no-go) as repeated-measures. Mean correct RTs and ERs of T3 were submitted to an ANOVA with SOA (50 vs. 1,000 ms) as a repeated measure. Additionally, throughout the article, we provide results from Bayesian analyses (Masson, 2011; Wagenmakers, 2007) when critical conclusions are based on nonsignificant results. ERs for T3 were calculated separately for erroneously withheld responses in case of a go trial (go trial errors) and for erroneously given responses in case of a no-go trial (no-go trial errors).

Results

All mean RTs are visualized in Figure 4 (see also Table 1) and ERs are summarized in Table 1.

Task 1. The ANOVA for mean RT1s (2.85% outliers) yielded no significant results, all Fs ≤ 1.63, all ps $\geq .214$. The ANOVA for ER1 yielded a significant main effect of SOA, with 1.59% more errors for the 50 ms SOA compared with the 1,000 ms SOA, $F(1, 23) = 18.02$, $p < .001$, $\eta_p^2 = .44$. All other Fs ≤ 0.41, all ps $\geq$ .527.

Task 2. The ANOVA for mean RT2s (2.88% outliers) revealed a significant main effect of SOA, with 640 ms shorter RT2s for the 1,000 ms SOA relative to the 50 ms SOA, that is, the typical PRP effect for T2, $F(1, 23) = 323.63$, $p < .001$, $\eta_p^2 = .93$. Further, the ANOVA revealed a main effect of trial type, with 41 ms shorter RT2s for go compared with no-go trials, reflecting the no-go BCE in T2, $F(1, 23) = 13.71$, $p = .001$, $\eta_p^2 = .37$. The interaction, however, was not significant, which indicates that the no-go BCE was of comparable size at both SOAs, $F(1, 23) = 2.45$, $p = .131$, $\eta_p^2 = .10$ ($BF_{01} = 1.45$, $p_{BIC}(H_0|D) = .592$). Descriptively, the no-go BCE was slightly *larger* at the short (51 ms) compared with the long SOA (31 ms), instead of being underadditive. No significant effects were observed for ER2, all Fs ≤ 0.31, all ps $\geq .769$.

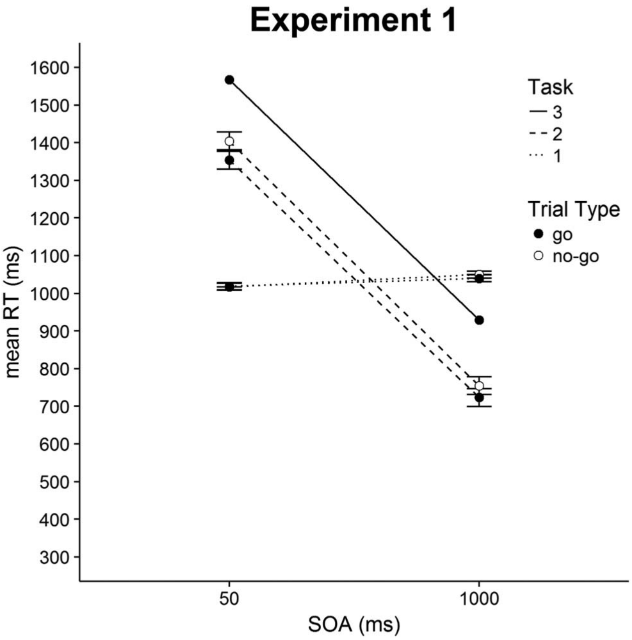

Figure 4. Mean RTs of Tasks 1, 2 and 3 as a function of trial type (go vs. no-go) and SOA (50 ms vs. 1,000 ms) for Experiment 1. For Task 1 and 2, errors bars are 95% within-subject confidence intervals for the difference between go and no-go trials, collapsed across SOA (see Pfister & Janczyk, 2013). Note that this does not apply for mean RTs of Task 3 because no RTs for no-go responses can be measured. Thus, error bars for Task 3 were omitted.

Task 3. The ANOVA for mean RT3s (2.98% outliers) revealed a main effect of SOA, with 638 ms shorter RT3s at the SOA of 1,000 ms compared with an SOA of 50 ms, $F(1, 23) = 298.89$, $p < .001$, $\eta_p^2 = .93$. The ANOVA for go-trial errors revealed a significant effect of SOA, $F(1, 23) = 4.80$, $p = .039$, $\eta_p^2 = .17$, with 0.43% less errors for the 1,000 ms SOA compared with the 50 ms SOA. The main effect of SOA was not significant for no-go trial errors, $F(1, 23) = 0.58$, $p = .453$, $\eta_p^2 = .02$.

Discussion

Experiment 1 aimed to determine whether the no-go BCE arises (a) before or (b) at or after the bottleneck by means of applying the *locus of slack logic*. A no-go BCE was observed in T2, but its size did not differ across SOAs. Thus, the no-go BCE was *not* absorbed into slack meaning that a locus of the no-go BCE before the bottleneck could be excluded. Even though the additional Bayes analysis revealed only positive evidence favoring the H_0, it is important to note that the (descriptive) data pattern does not point to an underadditive interaction of SOA and trial type (that would in fact have been problematic for the conclusion from this experiment). Thus, the results observed in Experiment 1 contradict the assumption that the no-go BCE is located inside RA as implied by Röttger and Haider (2017). If one assumes the compatibility-based and the no-go BCE were caused by the same mechanisms, this experiment could be conceived as a replication of Experiments 1–3 of Janczyk et al. (2017). To further distinguish between (a) a locus before or during the bottleneck or (b) after the bottleneck in the motor stage, Experiments 2 and 3 applied variants of the *effect propagation logic*.

Experiment 2

To apply the *effect propagation logic* (see, e.g., Kunde, Pfister, & Janczyk, 2012; Miller & Reynolds, 2003) in Experiment 2, the order of tasks in Experiment 1 was switched. The two tasks in between which backward crosstalk was enabled were now presented first: T1 (the identity task) was the task for which the no-go BCE was observed, and T2 (the color task) was the go/no-go task causing the no-go BCE in T1. The former T1 was now T3 (the tone task), and was separated from T1 and T2 by the SOA.

For the following argument, we assume that the SOA is short (i.e., 50 ms). Consider first the case that a stage before the motor stage is the locus of the no-go BCE in T1 (against the background of Experiment 1, this would be the RS stage). Any prolongation of these stages in T2 no-go trials delays the start of T2 RS and thereby also of T3 RS in a no-go trial.[5] The situation, however, is slightly more complicated because the RS stage of no-go tasks is known to be shorter than of go tasks (de Jong, 1993; Van Selst & Johnston, 1997). This counteracts

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[5] Note that our reasoning hinges on the assumption that the processing of no-go tasks also need a RS stage, and there is ample evidence for this assumption (Bertelson & Tisseyre, 1969; de Jong, 1993; Gottsdanker, 1979; Kerr, 1983; Smith, 1967; Van Selst & Johnston, 1997).

Table 1
Mean RTs (in Milliseconds) and Error Rates (ER, in %) for Experiment 1 as a Function of Trial Type and SOA (in Milliseconds)

			Trial type		
DV	Task	SOA	Go	No-go	BCE
RT					
	Task 1	50	1,019	1,017	−2
		1,000	1,040	1,049	10
	Task 2	50	1,353	1,404	51
		1,000	723	755	31
	Task 3	50	1,567	—	—
		1,000	930	—	—
ER					
	Task 1	50	3.86	4.13	.27
		1,000	2.50	2.32	.18
	Task 2	50	2.47	2.69	.22
		1,000	2.75	2.71	−.05
	Task 3	50	.57	1.21	—
		1,000	.13	.97	—

Note. DV = dependent variable; SOA = stimulus onset asynchrony; BCE = backward crosstalk effect. Crosstalk effects were computed by subtracting values from go trials from those of no-go trials line-by-line.

the propagation from T1 and two situations are possible: (a) If the RS stage is the locus and if T2 RS is strongly shortened, the propagation may be outweighed and RT3s are even shorter in no-go compared with go trials ("inverted no-go BCE"; see Figure 5a, left panel). (b) With a moderately shortened T2 RS stage, the T3 effect is in the same direction as for T1, but smaller (see Figure 5b, left panel).

The second possible case is that the motor stage after the bottleneck is the locus of the no-go BCE. The prolongation of this stage would only affect RT1 and, thus, T2 RS and T3 RS should not be delayed (see Figure 5, right panels). Regardless of how much T2 RS is shortened, the onset of T3 RS is earlier in no-go trials than in go trials and an inverted no-go BCE in T3 would be observed.

With the long SOA of 1,000 ms, no effect of the T2 go/no-go manipulation is expected instead. Taken together, a propagation of the T1 no-go BCE into T3 (although of a smaller size in T3) would suggest a locus of the BCE in RS. An inverted no-go BCE would, however, be compatible with a RS and a motor locus, and further conclusions are difficult in this case. Nonetheless, we ran this rather standard effect propagation experiment for two reasons: First, it is an empirical question whether we would observe a propagated standard BCE in T3, which is only predicted assuming a RS locus (Figure 5b, left panel). Second, regardless of the outcome, the results pattern will indicate whether the models illustrated in Figure 5 can in principle make correct predictions in this novel experimental situation.

Method

Participants. Twenty-four students (14 women) from the University of Tübingen, aged 19 to 36 years (*M* = 23.1 years, *SD* = 3.7), participated for monetary compensation (8€) or course credit. All participants provided written informed consent before the experiment and had normal or corrected-to-normal vision.

Apparatus, stimuli, task, procedure, and analysis. Experiment 2 was almost the same as Experiment 1. The only change concerned the order of the tasks, and for an illustration of the following, see Figure 3a and 3c. T1 was now to respond to the letter identity (S1) via a manual keypress of one of two response keys located to the left of the participant, using the left index and middle finger (R1). T2 was the go/no-go response to the color of the letter (S2) via a keypress of a single response key located to the right of the participant with the right index finger (R2). Task 3 was to respond to the tone via the vocal utterance (R3).

The procedure was very similar to Experiment 1. The order of stimulus presentation was now changed, with S1 and S2 arriving first. After the SOA, the tone was presented as S3. A trial was considered a go trial when R2 was to be given; otherwise it was considered a no-go trial. Instructions, practicing blocks, and error messages were adapted to the new tasks.

T1 and T3 mean correct RTs and ERs were submitted to 2 × 2 ANOVA with SOA (50 vs. 1,000 ms) and trial type (go vs. no-go) as repeated-measures. Mean correct RTs and ERs of T2 were submitted to an ANOVA with the factor SOA (50 vs. 1,000 ms) as a repeated measure.

Results

All mean RTs are visualized in Figure 6 (see also Table 2) and ERs are summarized in Table 2.

Task 1. The ANOVA for mean RT1s (2.86% outliers) yielded a significant main effect of SOA, with 40 ms shorter RTs at the 1,000 ms SOA compared with the 50 ms SOA, $F(1, 23) = 13.25$, $p = .001$, $\eta_p^2 = .37$. Further, a significant main effect of trial type was observed with 26 ms shorter RTs for go relative to no-go trials, that is, a no-go BCE, $F(1, 23) = 9.69$, $p = .005$, $\eta_p^2 = .30$. A significant interaction was observed, with a 18 ms larger no-go BCE at the 50 ms SOA compared with the 1,000 ms SOA, $F(1, 23) = 4.55$, $p = .044$, $\eta_p^2 = .17$. The analysis for ER1 yielded no significant effect, all $F\text{s} \leq 2.34$, all $p\text{s} \geq .140$.

Task 2. The ANOVA for mean RT2s (3.0% outliers) yielded no significant main effect of SOA, $F(1, 23) = 2.97$, $p = .098$, $\eta_p^2 = .11$. The main effect of SOA was significant for go errors, with 0.49% less errors at the 1,000 ms SOA relative to the 50 ms SOA, $F(1, 23) = 4.98$, $p = .036$, $\eta_p^2 = .18$. The main effect of SOA only approached significance for no-go trial errors, $F(1, 23) = 3.94$, $p = .059$, $\eta_p^2 = .15$.

Task 3. The ANOVA for mean RT3s (2.9% outliers) revealed a main effect of SOA, with 361 ms shorter RT3s at the 1,000 ms SOA compared with the 50 ms SOA, $F(1, 23) = 192.42$, $p < .001$, $\eta_p^2 = .89$. Most crucially, a significant main effect of trial type was obtained, with 58 ms shorter RT3s for no-go trials compared with go trials, indicating an *inverted* no-go BCE, $F(1, 23) = 41.80$, $p < .001$, $\eta_p^2 = .65$. Further, the inverted no-go BCE at the 50 ms SOA was −115 ms large, while it was not present at the 1,000 ms SOA (0 ms), $F(1, 23) = 54.27$, $p < .001$, $\eta_p^2 = .70$. The ANOVA for ER3 revealed a significant main effect of SOA, $F(1, 23) = 10.80$, $p = .003$, $\eta_p^2 = .32$, with 1.37% more errors at the 50 ms compared with the 1,000 ms SOA. All other $F\text{s} \leq 1.39$, all $p\text{s} \geq .250$.

Discussion

The purpose of Experiment 2 was to distinguish between a locus of the no-go BCE (a) before the motor stage or (b) in the motor

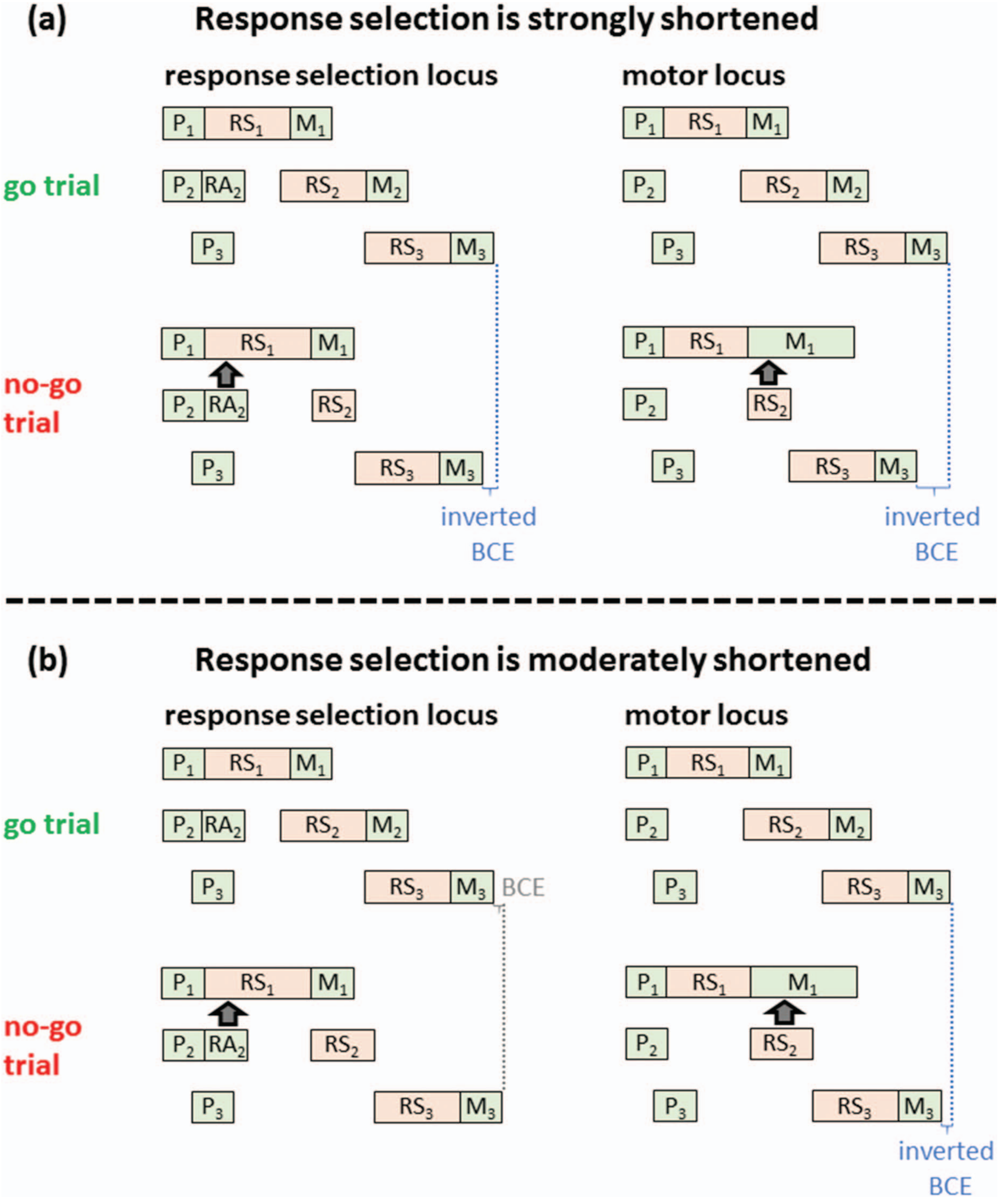

Figure 5. Illustration of the extended PRP paradigm applying the effect propagation logic with a short SOA (see Janczyk et al., 2017). Panel (a) illustrates the case when the response selection (RS) stage of Task 2 is shortened by a *large* amount, in the case of a RS and motor (M) locus of the no-go BCE. Because of the shortened RS in Task 2 the no-go backward crosstalk effect (BCE) is *inverted*. The inverted no-go BCE is smaller in the case of a RS locus compared with a M locus. Panel (b) illustrates the case when RS of Task 2 is shortened by a *small* amount, in the case of a RS or a M locus of the no-go BCE. Despite the minimally shortened RS in no-go trials the no-go BCE should be present in the case of a RS locus. In the case of a M locus, however, the no-go BCE should still be inverted. See the online article for the color version of this figure.

stage by applying the *effect propagation logic*. Now the no-go BCE was observed in T1 and was caused by T2 which was a go/no-go task. After a variable SOA, a two-choice T3 was presented. Complicating the situation, T2 RS is known to be shorter for no-go trials relative to go trials and, thus, a reversal of the no-go BCE was possible for T3 (see Figure 5), and both possible loci are able to predict this. If, on the other hand, a decreased (but not inverted) no-go BCE in T3 relative to T1 would be observed, a locus before the motor stage would be indicated.

Results indeed revealed a reversal of the no-go BCE at the 50 ms SOA, while at the 1,000 ms SOA any differences were eliminated, as predicted. This pattern of results first suggests that in general the models assuming a shortened RS stage make correct predictions if they also assume a motor locus as depicted in Figure 5 (right half of the panel). On the other hand, models assuming a RS locus only make correct predictions if the RS stage in no-go tasks is shortened by a large amount (Figure 5, upper left panel), which can be tentatively interpreted as first evidence against a locus before motor execution because it makes a locus in motor execution more likely. However, because the no-go BCE was inverted in T3, the data do not allow for distinguishing both loci with certainty because it is unknown by how much the T2 RS is shortened in no-go trials, which determines the size of the inverted no-go BCE. Looking at the mean RTs in Figure 6, the rather large inverted BCE seems most compatible with the predictions made in Figure 5a (right panel), that is, a motor locus. Note also that there is a slight modulation of the no-go BCE in Task 1 by SOA, but frankly we have no convincing explanation for this unexpected observation. With the preliminary conclusion in favor of a motor locus in mind, we ran Experiment 3 where the inverted no-go BCE was compared with a proper baseline condition.

Table 2
Mean RTs (in Milliseconds) and Error Rates (ER, in %) for Experiment 2 as a Function of Trial Type and SOA (in Milliseconds)

DV	Task	SOA	Trial type Go	 No-go	 BCE
RT					
	Task 1	50	607	642	35
		1,000	576	593	18
	Task 2	50	814	—	—
		1,000	792	—	—
	Task 3	50	1,266	1,151	−.115
		1,000	848	847	0
ER					
	Task 1	50	2.39	2.42	.03
		1,000	2.97	2.63	−.34
	Task 2	50	.88	1.17	—
		1,000	.39	.66	—
	Task 3	50	3.17	3.37	.19
		1,000	1.66	2.14	.48

Note. DV = dependent variable; SOA = stimulus onset asynchrony; BCE = backward crosstalk effect. Crosstalk effects were computed by subtracting values from go trials from those of no-go trials line-by-line. Negative results indicate a (numerically) inverted BCE.

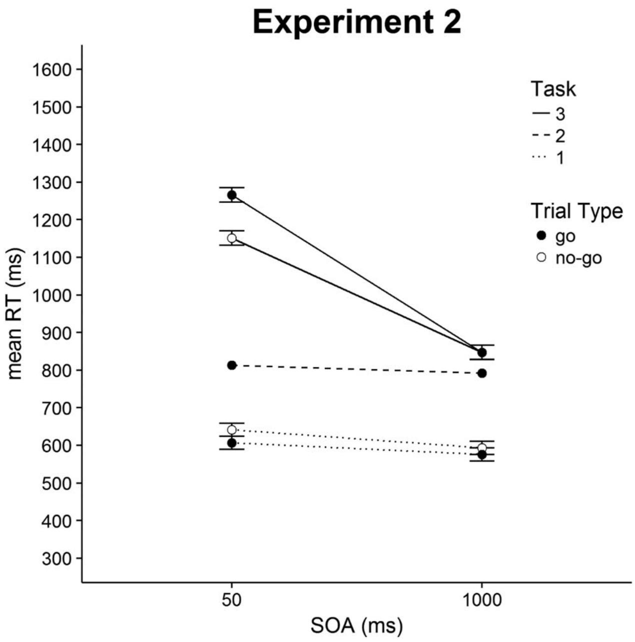

Figure 6. Mean RTs of Tasks 1, 2, and 3 as a function of trial type (go vs. no-go) and SOA (50 ms vs. 1,000 ms) for Experiment 2. Errors bars are 95% within-subject confidence intervals for the difference between go and no-go trials, collapsed across SOA (see Pfister & Janczyk, 2013). Note that this does not apply for mean RTs of Task 2 because no RTs for no-go responses can be measured. Thus, error bars for Task 2 were omitted.

Experiment 3

The inverted no-go BCE observed in T3 of Experiment 2 is in line with both possible loci. Its exact size, however, depends on the locus of the no-go BCE, but without a proper baseline, this is difficult to evaluate. As can be seen in Figure 7 (middle panel), in the case of a motor locus, RS2 and RS3 are not delayed and the inverted no-go BCE reflects only the difference in T2 RS duration between go- and no-go trials. In the case of a locus before the motor stage, however, RS2 and RS3 are delayed as well (see Figure 7, left panel). In summary, the inverted BCE in T3 is the result of the differences in T2 RS but also of the propagated effect from T1 and, thus, a *smaller* inverted no-go BCE is predicted by a locus before the motor stage.

To establish a baseline against which we can compare the size of the inverted BCE in T3, in Experiment 3 the number of tasks in each trial was manipulated *block-wise*. Half of all blocks comprised three tasks similar to Experiment 2 (see Figure 7, left and middle panel). In the other half of blocks, T1 (the identity task) was omitted and a trial comprised only two tasks (i.e., T2 [the color task] and T3 [the tone task]; see Figure 7, right panel). Again, the same task order as in Experiment 2 was applied; however, the integral stimulus for T1 (identity of the letter) and T2 (color of the letter) had to be changed to two separate stimuli, to allow for an omission of S1 without also omitting S2. Thus, instead of using a colored letter, a colored square (S2) surrounding the letter (S1) was now introduced.[6] Data from

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[6] To make sure the new stimulus material would also elicit the no-go BCE in T1, a pilot study ($n = 8$) was conducted before running Experiment 3. Applying only T1 and T2 the no-go BCE was still observed in RT1, $F(1,7) = 9.47$, $p = .018$, $\eta_p^2 = .57$, and the new S1/S2 combination appeared reasonable to be used in Experiment 3.

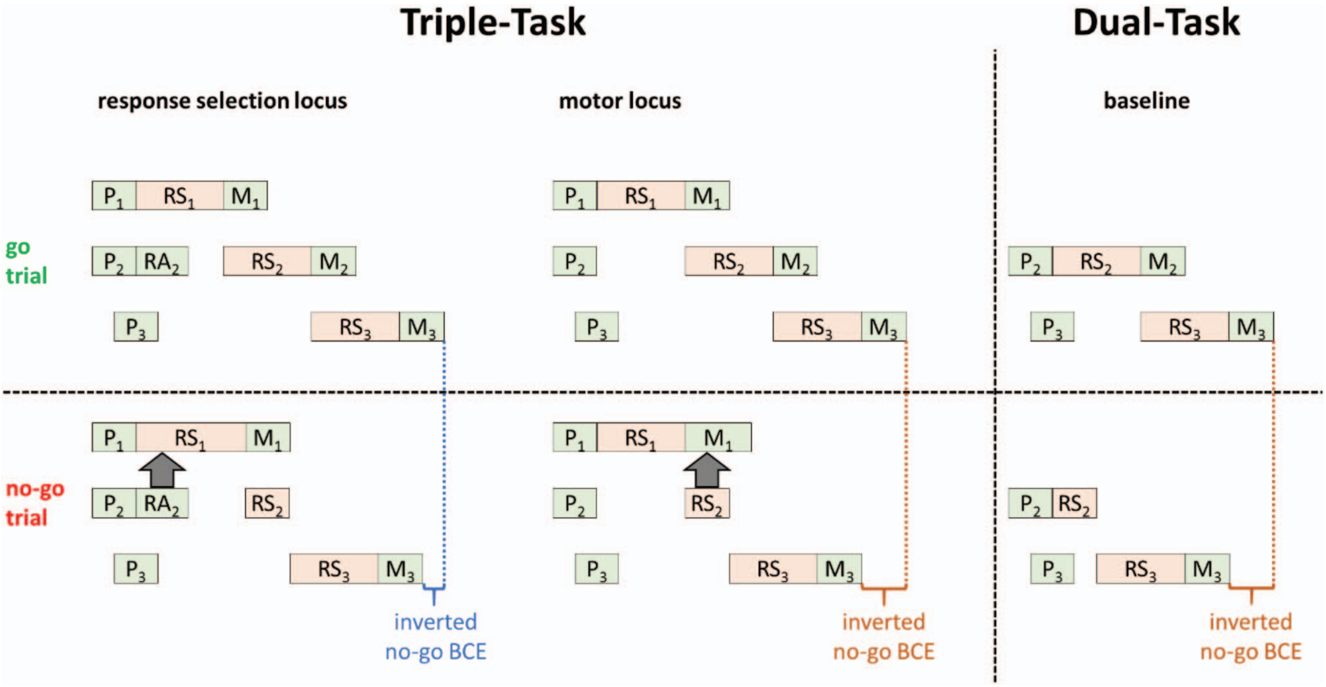

Figure 7. Illustration of the extended PRP paradigm applying the effect propagation logic (see Janczyk et al., 2017). The left side of the panel illustrates the predictions for the inverted no-go BCE in Task 3 for the triple-task condition. The predictions are based on the response selection bottleneck model under assumption of either a response selection or motor locus. In the case of a response selection locus a *small* inverted no-go BCE is predicted, because of the prolonged response selection stage in Task 1 of no-go trials. Note, that a response activation stage is needed in Task 2 to enable backward crosstalk (see Janczyk et al., 2017; Thomson et al., 2015). In the case of a motor locus, however, the prolongation of the motor stage of Task 1 does not delay the onset of Task 3 response selection in no-go trials and, thus, a *large* inverted no-go BCE is predicted. The right side of the panel illustrates the prediction for the inverted no-go BCE in Task 3 for the dual-task baseline. In the baseline condition no BCE arises in Task 1 and, thus, the inverted no-go BCE in Task 3 only depends on the shortening of Task 2 response selection in no-go relative to go trials. Note that assuming a motor locus the response selection bottleneck model predicts the same effect size of the inverted no-go BCE as the dual-task baseline (the *small* inverted no-go BCE predicted by a response selection locus is visualized by the blue curly bracket and the large inverted no-go BCE predicted by a motor locus and the dual-task baseline are visualized by the orange curly bracket). See the online article for the color version of this figure.

dual-task blocks were used as baseline for the inverted no-go BCE in T3, because the inverted BCE would only reflect the differences in T2 RS depending on the go or no-go status of a trial. A comparison of the inverted no-go BCE in the triple- and dual-task blocks would then allow to distinguish both possible loci of the no-go BCE. If the size of the inverted no-go BCE in T3 is the same in the triple-task and the dual-task condition, a locus of the no-go BCE in the motor stage is indicated. If, however, the inverted no-go BCE in the triple-task is smaller relative to the dual-task condition, a locus before the motor stage is indicated.

Because of the additional manipulation of dual versus triple-task and because the data from the long SOA of 1,000 ms is not indicative in the present experiment, we applied only a short SOA of 50 ms. Note that in Experiment 2, the long SOA was used and yielded the expected results patterns.

Method

Participants. Thirty-two students (29 women) from the University of Tübingen, aged 19 to 36 years ($M = 22.9$ years, $SD = 3.2$), participated for monetary compensation (8€) or course credit. All participants provided written informed consent before the experiment and had normal or corrected-to-normal vision.

Apparatus, stimuli, task, procedure, and analysis. Experiment 3 was very similar to Experiment 2. The major changes concerned the stimulus material, and for an illustration of the following, see Figure 3a and 3d. T1 was now to respond to a white letter's identity (S1) via a manual keypress of one of two response keys located to the left of the participant, using the left index and middle finger (R1). T2 was now a go/no-go response to the color of a square surrounding the letter (S2) via a keypress of a single response key located to the right of the participant with the right index finger (R2). T3 was to respond to the tone via the vocal utterance (R3).

The procedure was nearly the same as in Experiment 2. In each trial S1 and S2 arrived first. However, S1 only appeared in half of all blocks (triple-task blocks) and was omitted in the other half of all blocks (dual-task blocks). After a constant SOA of 50 ms, the tone was presented. As in Experiment 2, a trial was considered a go trial when R2 was to be given, and otherwise it was considered a no-go trial. Instructions, practicing blocks, and error messages were adapted to the new tasks. Triple-task and dual-task blocks alternated and the type of the first block was counterbalanced across participants. Before each block, participants were informed about whether they would have to respond to three or two tasks in the upcoming block, and the according S-R mappings were again mentioned. Participants were instructed to respond as quickly and accurately as possible.

T1 data were submitted to two ANOVAs with trial type as a repeated measure and T2 data were submitted to two ANOVAS with task as repeated measure. T3 data were submitted to two ANOVAs with task and trial type as repeated measures.

Results

All mean RTs are visualized in Figure 8 (see also Table 3), and ERs are summarized in Table 3.

Task 1. The ANOVA for mean RT1s (1.02% outliers) yielded a significant main effect of trial type, with 19 ms shorter RTs for go trials compared with no-go trials, $F(1, 31) = 6.89$, $p = .013$, $\eta_p^2 = .18$. The main effect of trial type was not significant for ER1, $F(1, 31) = 0.12$, $p = .728$, $\eta_p^2 < .01$.

Task 2. Mean RT2s (2.74% outliers) were on average 492 ms shorter in dual-task relative to triple-task blocks, $F(1, 31) = 250.12$, $p < .001$, $\eta_p^2 = .89$. Go-trial errors occurred 1.45% more frequently in dual-task relative to triple-task blocks, $F(1, 31) = 31.34$, $p < .001$, $\eta_p^2 = .50$. The main effect of task was not significant for no-go errors, $F(1, 31) = 3.55$, $p = .069$, $\eta_p^2 = .10$.

Task 3. The ANOVA for mean RT3 (2.64% outliers) revealed a significant main effect of trial type, with 159 ms shorter RT3s for no-go relative to go trials, $F(1, 31) = 117.53$, $p < .001$, $\eta_p^2 = .79$, indicating an inverted no-go BCE. Trivially, RT3s were on average 465 ms shorter in dual-task relative to triple-task blocks, $F(1, 31) = 149.93$, $p < .001$, $\eta_p^2 = .83$, but the interaction of trial type and task was not significant, $F(1, 31) = 0.06$, $p = .816$, $\eta_p^2 < .01$, indicating that the size of the inverted no-go BCE did *not* differ between the triple-task and dual-task blocks ($BF_{01} = 5.50$, $p_{BIC}(H_0|D) = .846$). The ANOVA for ER3 revealed a significant main effect of trial type, with on average 1.31% less errors in go trials compared with no-go trials, $F(1, 31) = 16.99$, $p < .001$, $\eta_p^2 = .35$, indicating a speed–accuracy trade-off. In dual-task blocks on average 1.53% less errors relative to triple-task blocks were observed, $F(1, 31) = 16.52$, $p < .001$, $\eta_p^2 = .35$. The interaction of trial type and task was not significant, $F(1, 31) = 0.01$, $p = .909$, $\eta_p^2 < .01$.

Speed-accuracy trade-off (SAT). The no-go BCE for ER3 opposed that for RT3s, indicating a SAT was present what complicates the interpretation of the RT3 results. To investigate whether the SAT modulated the pattern of results obtained for RT3, the method of Janczyk (2016) was adopted. To this end, no-go BCEs for RT3 and ER3 were calculated for each participant. If the signs of both BCEs did not match, an SAT for the respective participant was indicated. RT3 data were then submitted to a mixed ANOVA with trial type and task as repeated measures and the additional between-subjects factor SAT. Neither the main effect of SAT, $F(1, 30) = 1.13$, $p = .296$, $\eta_p^2 = .04$, nor the interaction of SAT and trial type, $F(1, 30) = 0.65$, $p = .426$, $\eta_p^2 = .02$, were significant ($BF_{01} = 4.01$, $p_{BIC}(H_0|D) = .801$). Most importantly, the interaction of SAT, trial type and task was not significant, $F(1, 30) = 0.10$, $p = .757$, $\eta_p^2 < .01$ ($BF_{01} = 5.37$, $p_{BIC}(H_0|D) = .843$). Even

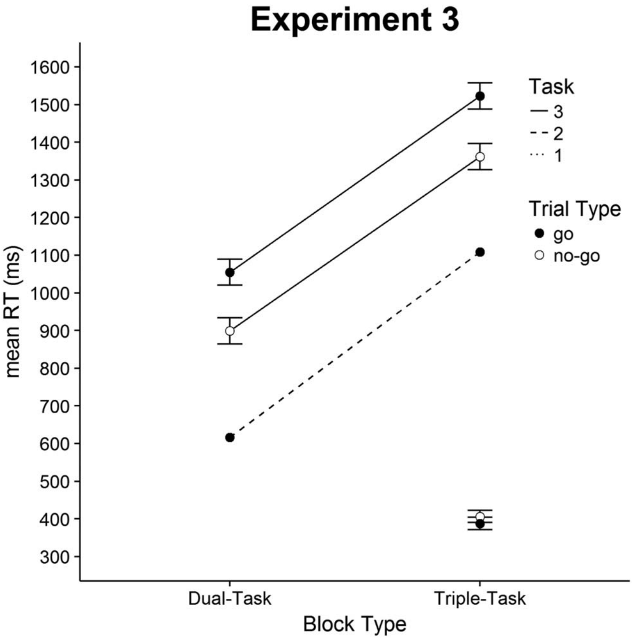

Figure 8. Mean RTs of Tasks 1, 2, and 3 as a function of trial type (go vs. no-go) and block type (dual-task vs. triple-task) for Experiment 3. Errors bars are 95% within-subject confidence intervals for the difference between go and no-go trials, collapsed across SOA (see Pfister & Janczyk, 2013). Note that this does not apply for mean RTs of Task 2 because no RTs for no-go responses can be measured. Thus, error bars for Task 2 were omitted.

Table 3
Mean RTs (in Milliseconds) and Error Rates (ER, in %) for Experiment 3 as a Function of Trial Type and Block Type

			Trial type		
DV	Task	Block type	Go	No-go	BCE
RT					
	Task 1	Dual-task	—	—	—
		Triple-task	388	406	19
	Task 2	Dual-task	616	—	—
		Triple-task	1,109	—	—
	Task 3	Dual-task	1,055	899	−.156
		Triple-task	1,523	1,362	−.161
ER					
	Task 1	Dual-task	—	—	—
		Triple-task	2.60	2.72	.12
	Task 2	Dual-task	1.75	1.57	—
		Triple-task	.30	.99	—
	Task 3	Dual-task	2.82	4.09	1.27
		Triple-task	4.32	5.66	1.34

Note. DV = dependent variable; SOA = stimulus onset asynchrony; BCE = backward crosstalk effect. Crosstalk effects were computed by subtracting values from go trials from those of no-go trials line-by-line. Negative results indicate an (numerically) inverted BCE.

additional separate analyses for data with and without an SAT yielded qualitatively similar results.

Discussion

The goal of Experiment 3 was to distinguish between a locus of the no-go BCE (a) before or (b) in the motor stage. However, a locus in RS and in motor execution both predict an inverted no-go BCE in T3, because of a significantly shortened T2 RS stage in no-go tasks (de Jong, 1993; Van Selst & Johnston, 1997; see also Experiment 2). As the observation of an inverted no-go BCE alone would not allow for distinguishing between a RS or motor execution locus, a dual-task baseline condition was implemented where the pure propagation from T2 to T3 without any additional propagation from T1 could be observed. As can be seen in Figure 7, the inverted no-go BCE predicted by a motor locus and by the baseline condition are of the same size. Thus, an inverted no-go BCE of the same size in the triple-task and dual-task baseline indicates a motor locus of the no-go BCE, whereas an inverted no-go BCE of a smaller size in the triple-task relative to the dual-task baseline indicates a RS locus of the no-go BCE.

Half of all blocks comprised a triple-task while the other half comprised dual-tasks (baseline condition). In the triple-task blocks a no-go BCE was expected to arise in T1. In T3 of triple-task and dual task blocks an *inverted* no-go BCE was expected. Results showed that the size of the inverted no-go BCE did *not* differ between the triple-task condition and the dual-task baseline. This result is in line with the predictions under the assumption of a motor locus of the no-go BCE. One incidental observation is the higher rate of go errors in the dual-task compared with the triple-task condition in T2. Frankly, we have no convincing explanation for this and prefer not to interpret this result.

General Discussion

The goal of the present study was to locate the no-go BCE inside the stages of the RSB model. Experiment 1 used the locus of slack logic to distinguish between a locus (a) before or (b) at or after the bottleneck. The no-go BCE arising in T2 was still present even at the 50 ms SOA and SOA and trial type combined additively. This suggests that the no-go BCE must be located at or after the bottleneck because it was not absorbed into the cognitive slack. Thus, a locus inside T1 RA could be ruled out. Subsequently, Experiment 2 was carried out to distinguish between a locus (a) before or (b) in the motor stage, by applying the effect propagation logic. The inverted no-go BCE in T3 was predicted by both loci though and, thus, no differentiation was possible merely on the basis of these data. In Experiment 3 the size of the inverted no-go BCE in T3 was compared with a dual-task baseline. Most importantly, the size of the inverted no-go BCE did not differ between both conditions, and data from Experiment 3 suggest a motor locus of the no-go BCE. This latter result again rules out a prebottleneck locus, because the used logic distinguishes a motor locus from an earlier one. Only if we had to conclude in favor of an earlier locus, a prebottleneck locus would be viable at all and the results from Experiment 1 provide the evidence for distinguishing the bottleneck from such prebottleneck stages. Taken together, these results suggest that the no-go BCE is located *after* the response selection stage and, thus, in the *motor execution stage*.

Theoretical Implications

To further investigate the underlying mechanisms of both types of the BCE a closer look at the overlapping processing stages enabling the no-go BCE is required. Recent studies investigating the compatibility-based BCE (Janczyk et al., 2017; Thomson et al., 2015) suggest that this BCE is caused by automatically accumulated T2 RA adding to evidence of T1 accumulated in RS (see Figure 1c). If an automatic accumulation of evidence for T2 were possible for the no-go BCE as well, this could only be the case inside T2 RA. However, an overlap between T1 motor execution and T2 RA hardly seems to have enabled the no-go BCE in the present study, because no temporal overlap of both stages was given in any of the three experiments.

Alternatively, a model in which T1 and T2 motor execution overlap could be debated. However, an overlap between two motor execution stages also seems implausible because in a strict interpretation of the RSB model there is no motor execution stage needed in no-go tasks, allowing no possibility for crosstalk (for a visualization see, Miller, 2017, Figure 1).

The most plausible model taking into account a motor execution locus of the no-go BCE is one with temporal overlap of T1 motor execution and T2 response selection (see Figure 1d for an illustration). In all three experiments of the present study, the task in which the no-go BCE was observed and the task causing the no-go BCE were presented simultaneously. Thus, it can be assumed that the onset of T1 motor execution coincided with the onset of T2 RS. This model is partially supported by results of other studies applying the PRP paradigm (Miller, 2006, Experiment 1) and the PP paradigm (Miller & Durst, 2015, Experiment 1). Miller (2006) observed a no-go BCE even at the shortest SOA of 100 ms and there was no modulation of the no-go BCE with increasing SOA (100, 200, or 400 ms). This result was replicated by Miller and Durst (2015) who even intermixed negative SOAs (that means that T2 arrived first) with positive SOAs (−400, −150, 0, 150, and 400 ms). If the overlap of T1 motor execution with any T2 stage before RS would enable the no-go BCE, then the no-go BCE should have become larger with increasing SOA and the no-go BCE should not be observed at short or even negative SOAs (because T2 RA would have taken place during the cognitive slack).

Two Types of Backward Crosstalk

A motor execution locus of the no-go BCE contrasts with the results of recent studies which located the locus of the compatibility-based BCE inside RS (Janczyk et al., 2017; Miller, 2017; Thomson et al., 2015). Taken together, different loci for both types of the BCE suggest that the compatibility-based BCE and the no-go BCE are based on different cognitive processes and, therefore, represent qualitatively different types of BCEs.

The compatibility-based BCE is enabled when T1 RS and T2 RA overlap (Janczyk et al., 2017; Thomson et al., 2015). Janczyk et al. (2017) recently suggested that RA could occur in T2, if it does not gain direct access to RS (see Figure 1c). This evidence then adds to the evidence for T1, which is accumulated in a *controlled* manner in RS and, thus, prolongs the RS stage of T1 in incompatible trials (see Ulrich, Schröter, Leuthold, & Birngruber, 2015, for this idea in the case of conflict tasks). In a sense then, the compatibility-based BCE may work similar as other conflict tasks (e.g., the Eriksen flanker task; Eriksen & Eriksen, 1974).

The no-go BCE, in contrast, seems to be based on a different mechanism. A model where temporal overlap between T1 motor execution and T2 response selection enables the no-go BCE implies that processing of a no-go T2 involves a controlled RS process (for general evidence for the presence of a controlled RS stage in no-go tasks, see Bertelson & Tisseyre, 1969; Gottsdanker, 1979; Kerr, 1983; Smith, 1967). This is in contrast to the assumption that a no-go task can become automatized with practice (Röttger & Haider, 2017; Verbruggen & Logan, 2008), because RS is by definition a controlled process. Verbruggen and Logan (2008) argued that in the go/no-go paradigm each stimulus is consistently associated with either a go or no-go goal that should enable automatic inhibition of an already prepared response with practice. Such no-go goals could for instance be the perception of a sensory consequence of not responding (see Kühn et al., 2009). Verbruggen and Logan observed that RTs were prolonged when S-R mappings were switched and when stimuli previously had been consistently associated to go/no-go responses in the training phase. They concluded that, with practice, stimulus no-go associations get strong enough to automatically inhibit an already prepared response by activating the no-go goal upon retrieval of the stimulus no-go association.

Analogous to Verbruggen and Logan (2008), post hoc analyses were carried out to test whether the inhibition of an already prepared response became automatic with practice in the present study.[7] The results indicated that inhibition did *not* become automatic in the present study, which provides further support for the assumption that a *controlled* response selection process is needed to process no-go tasks.

In a nutshell, we suggest that both types of the BCE have different prerequisites and are based on different cognitive processes—that means they have different sources. The compatibility-based BCE is based on *automatic* response feature activation and is enabled when T1 RS and T2 RA overlap, whereas the no-go BCE is based on a *controlled* process and is enabled when T1 motor execution and T2 RS overlap. Even though on a phenomenological level both types of the BCE appear to be similar, they fundamentally differ in the underlying cognitive processes, as the compatibility-based BCE has its source in T2 RA whereas the no-go BCE has its source in T2 RS. Thus, it can be concluded that backward crosstalk is *not* a general phenomenon itself. The term "backward crosstalk" should rather be used as an umbrella term for different types of crosstalk, which can be further specified as compatibility-based BCEs or no-go BCEs. As a possible objection, however, we had the go/no-go task always in the setting of a dual-task (or even triple-task) experiment. We cannot exclude that this particular context has induced some controlled processing that overrode automaticity, for example, because of the required control of task order. Future research may investigate whether the task's characteristics depend on whether it is performed in isolation or in a multitasking context.

Caveats, Limitations, and Future Directions

The results of the present study appear straightforward. However, it should be noted that the assumptions made and the implications drawn from the present study hinge on a strictly serial interpretation of the RSB model, where the stage affected by the no-go BCE is prolonged. This strictly serial interpretation of the RSB model was chosen in line with the available literature (see, e.g., Eder, Pfister, Dignath, & Hommel, 2016; Hommel & Eglau, 2002; Lien & Proctor, 2002; Paelecke & Kunde, 2007). As alternative interpretations cannot be excluded yet, further research applying alternative methods is needed. For instance data from diffusion models (e.g., Ulrich et al., 2015) could help to review the conclusions drawn from the present study, and such work is currently ongoing in our lab. Additionally, we assumed the bottleneck in the RS stage, but we concur that there are other models suggesting, for example, a motor bottleneck instead or in addition to the RS bottleneck (see Bratzke et al., 2008; de Jong, 1993).

Following the strictly serial interpretation of the RSB model, the question upon which controlled process the no-go BCE is actually based still remains to be answered. Even though this question is clearly out of the scope of the present study, the present results can help to narrow down possible explanations. In this respect two processes could be discussed: (a) selection of the no-go response as one of two response alternatives (give the response vs. withhold the response) analogous to two-choice tasks, and (b) inhibition of an already prepared response. If the selection of a go versus no-go response takes place during the T2 RS stage of a no-go task analogous to the selection of a response in a two-choice task (for evidence that go/no-go and two-choice tasks are based on similar cognitive processes, see Gomez, Ratcliff, & Perea, 2007), the length of T2 RS should be the same irrespective of whether T2 is a go or no-go task. However, previous studies provided evidence that T2 RS is shortened by a significant amount in no-go relative to go trials (see also de Jong, 1993; Van Selst & Johnston, 1997), and the inverted no-go BCE in our Experiments 2 and 3 most likely arises exactly for this reason.

Alternatively, the shorter RS for no-go relative to go trials could indicate that the controlled process occurring in RS is actually the inhibition of the already prepared go response: The inhibition needed to withhold this response could in turn also prolong RT1 by inhibiting T1 motor execution (for similar suggestions see Ko & Miller, 2014; Miller & Durst, 2014). Furthermore, Janczyk and Huestegge (2017) observed that a no-go BCE in T1 could be inverted when preparation of T2 was impeded (i.e., by an increase of task relevant dimensions). The no-go BCE only emerged in their Experiment 3b where T2 always was a simple go/no-go task where the (correct) response in case of go trials could be entirely prepared and, thus, required inhibition in case of a no-go trial. Even though the available evidence and the present data indicate that inhibition of a prepared response could be the controlled process occurring during T2 RS, further research is needed to test this assumption.

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[7] To test whether inhibition of an already prepared task became automatic with practice in the present study, two post hoc ANOVAs for RT3s of Experiment 2 and 3 were carried out, including the additional within-subjects factor of block number. If the inhibition of an already prepared response became automatic with practice, there would no longer be a need for a RS stage in no-go tasks that would allow for an even earlier onset of T3 RS. Thus, an increase of the effect size of the inverted no-go BCE should be observed, if the inhibition of an already prepared response in T2 became automatic. However, neither the analyses for Experiment 2, $F(7,133) = 0.88$, $p = .524$, $\eta_p^2 = .04$, nor for Experiment 3, $F(7,217) = 0.31$, $p = .767$, $\eta_p^2 = .01$, $\varepsilon = .34$, yielded a significant interaction of trial type and block number. Thus, it can be concluded that inhibition of an already prepared response did *not* become automatic with practice in the present study.

It should be mentioned that a shortened T2 RS may not have been the only factor that contributed to the inverted no-go BCE, but interference from the motor execution of R2 may also have played a role. However, because T2 and T3 are the same in both conditions, such interference would be present in the triple-task but also in the dual-task baseline condition of Experiment 3. Thus, even if it contributed to the inverted no-go BCE, its contribution was the same in the triple-task and dual-task condition. Further, the comparison of the dual-task baseline and the triple-task condition in Experiment 3 was within-subjects to avoid further differences between both conditions.

Another potentially critical factor for the comparison of dual-task and triple-task blocks in Experiment 3 is that preparation may have differed in the two conditions. We have purposefully opted for a block-wise manipulation instead of omitting T1 trial-wise and randomly. Gottsdanker (1979) used the latter way and observed even longer RT2s without T1 that "suggests that the infrequent omission of S1 may have caused a strong surprise reaction that interfered with S2 processing" (de Jong, 1993, p. 4). Still, we cannot exclude that differential preparation took place. Even though it is unclear which processing stage would be modulated by preparation, it is reasonable to assume that better prepared stages were shorter in the dual-task compared with the triple-task condition. Assuming that such preparation affects the same stages of all tasks then, the inverted no-go BCE in the dual-task condition should still be of the same size no matter which processing stage is shortened. This can be illustrated by looking at Figure 7 (dual-task panel): Regardless of which stage is shortened in all tasks, the inverted no-go BCE does not change its size. Thus, such cases of preparation would be unproblematic for our interpretations. Note further that even enhanced preparation for T1 in the PP paradigm (Miller & Durst, 2014) led to in general very similar results as observed with the PRP paradigm, even when T1 was a no-go task (Miller & Durst, 2015). Nevertheless, future studies may further investigate a potential influence of motor execution-based interference of a go/no-go task and preparation on the inverted no-go BCE.

In summary, results of the present study clearly indicate that the compatibility-based and the no-go BCE are not only different types of backward crosstalk but also affect different stages of Tl processing. However, it cannot be said whether these models generalize to even other types of BCEs. For instance, performance in T1 can also be affected by T2 response complexity (Miller, 2006).

Conclusion

The present study suggests that the no-go BCE arises in the motor execution stage and a model with overlapping T1 motor execution and T2 RS appears to be best suited to explain this. In a broader picture, the loci and sources of the compatibility-based BCE and the no-go BCE differ fundamentally, and we suggest to use the term backward crosstalk only as an umbrella term, but to further specify distinct types of such effects.

References

Bertelson, P., & Tisseyre, F. (1969). Refractory period of c-reactions. *Journal of Experimental Psychology, 79,* 122–128. http://dx.doi.org/10.1037/h0026899

Bissett, P. G., Nee, D. E., & Jonides, J. (2009). Dissociating interference-control processes between memory and response. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35,* 1306–1316. http://dx.doi.org/10.1037/a0016537

Bratzke, D., Ulrich, R., Rolke, B., Schröter, H., Jentzsch, I., & Leuthold, H. (2008). Motor limitation in dual-task processing with different effectors. *Quarterly Journal of Experimental Psychology, 61,* 1385–1399. http://dx.doi.org/10.1080/17470210701536856

Brunia, C. H. (1983). Motor preparation: Changes in amplitude of Achilles tendon reflexes during a fixed foreperiod of one second. *Psychophysiology, 20,* 658–664. http://dx.doi.org/10.1111/j.1469-8986.1983.tb00935.x

de Jong, R. (1993). Multiple bottlenecks in overlapping task performance. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 965–980. http://dx.doi.org/10.1037/0096-1523.19.5.965

Donders, F. C. (1969). On the speed of mental processes. *Acta Psychologica, 30,* 412–431. http://dx.doi.org/10.1016/0001-6918(69)90065-1

Eder, A. B., Pfister, R., Dignath, D., & Hommel, B. (2016). Anticipatory affect during action preparation: Evidence from backward compatibility in dual-task performance. *Cognition and Emotion, 31,* 1211–1224.

Ellenbogen, R., & Meiran, N. (2008). Working memory involvement in dual-task performance: Evidence from the backward compatibility effect. *Memory & Cognition, 36,* 968–978. http://dx.doi.org/10.3758/MC.36.5.968

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics, 16,* 143–149. http://dx.doi.org/10.3758/BF03203267

Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions: A latent-variable analysis. *Journal of Experimental Psychology: General, 133,* 101–135. http://dx.doi.org/10.1037/0096-3445.133.1.101

Gomez, P., Ratcliff, R., & Perea, M. (2007). A model of the go/no-go task. *Journal of Experimental Psychology: General, 136,* 389–413. http://dx.doi.org/10.1037/0096-3445.136.3.389

Gottsdanker, R. (1979). A psychological refractory period or an unprepared period. *Journal of Experimental Psychology: Human Perception and Performance, 5,* 208–215. http://dx.doi.org/10.1037/0096-1523.5.2.208

Hazeltine, E., Teague, D., & Ivry, R. B. (2002). Simultaneous dual-task performance reveals parallel response selection after practice. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 527–545. http://dx.doi.org/10.1037/0096-1523.28.3.527

Heil, M., Osman, A., Wiegelmann, J., Rolke, B., & Hennighausen, E. (2000). N200 in the Eriksen-task: Inhibitory executive process? *Journal of Psychophysiology, 14,* 218–225. http://dx.doi.org/10.1027//0269-8803.14.4.218

Hommel, B. (1998). Automatic stimulus-response translation in dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 1368–1384. http://dx.doi.org/10.1037/0096-1523.24.5.1368

Hommel, B., & Eglau, B. (2002). Control of stimulus-response translation in dual-task performance. *Psychological Research, 66,* 260–273. http://dx.doi.org/10.1007/s00426-002-0100-y

Janczyk, M. (2013). Level 2 perspective taking entails two processes: Evidence from PRP experiments. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 39,* 1878–1887. http://dx.doi.org/10.1037/a0033336

Janczyk, M. (2016). Sequential modulation of backward crosstalk and task-shielding in dual-tasking. *Journal of Experimental Psychology: Human Perception and Performance, 42,* 631–647. http://dx.doi.org/10.1037/xhp0000170

Janczyk, M. (2017). A common capacity limitation for response and item selection in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 43,* 1690–1698. http://dx.doi.org/10.1037/xlm0000408

Janczyk, M., & Huestegge, L. (2017). Effects of a no-go Task 2 on Task 1 performance in dual - tasking: From benefits to costs. *Perception & Psychophysics, 79,* 796–806. http://dx.doi.org/10.3758/s13414-016-1257-6

Janczyk, M., Pfister, R., Hommel, B., & Kunde, W. (2014). Who is talking in backward crosstalk? Disentangling response- from goal-conflict in dual-task performance. *Cognition, 132,* 30–43. http://dx.doi.org/10.1016/j.cognition.2014.03.001

Janczyk, M., Pfister, R., Wallmeier, G., & Kunde, W. (2014). Exceptions to the PRP effect? A comparison of prepared and unconditioned reflexes. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40,* 776. http://dx.doi.org/10.1037/a0035548

Janczyk, M., Renas, S., & Durst, M. (2017). Identifying the locus of compatibility-based backward crosstalk: Evidence from an extended PRP paradigm. *Journal of Experimental Psychology: Human Perception and Performance*. Advance online publication. http://dx.doi.org/10.1037/xhp0000445

Kerr, B. (1983). Preplanning for aimed movements: Disruption from a preliminary task. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 596–606. http://dx.doi.org/10.1037/0096-1523.9.4.596

Ko, Y.-T., & Miller, J. (2014). Locus of backward crosstalk effects on task 1 in a psychological refractory period task. *Experimental Psychology, 61,* 30–37. http://dx.doi.org/10.1027/1618-3169/a000224

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility—A model and taxonomy. *Psychological Review, 97,* 253–270. http://dx.doi.org/10.1037/0033-295X.97.2.253

Kühn, S., Elsner, B., Prinz, W., & Brass, M. (2009). Busy doing nothing: Evidence for nonaction—Effect binding. *Psychonomic Bulletin & Review, 16,* 542–549. http://dx.doi.org/10.3758/PBR.16.3.542

Kunde, W., Pfister, R., & Janczyk, M. (2012). The locus of tool-transformation costs. *Journal of Experimental Psychology: Human Perception and Performance, 38,* 703–714. http://dx.doi.org/10.1037/a0026315

Lien, M.-C., & Proctor, R. W. (2000). Multiple spatial correspondence effects on dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 1260–1280. http://dx.doi.org/10.1037/0096-1523.26.4.1260

Lien, M.-C., & Proctor, R. W. (2002). Stimulus-response compatibility and psychological refractory period effects: Implications for response selection. *Psychonomic Bulletin & Review, 9,* 212–238. http://dx.doi.org/10.3758/BF03196277

Masson, M. E. J. (2011). A tutorial on a practical Bayesian alternative to null-hypothesis significance testing. *Behavior Research Methods, 43,* 679–690. http://dx.doi.org/10.3758/s13428-010-0049-5

Miller, J. (2006). Backward crosstalk effects in psychological refractory period paradigms: Effects of second-task response types on first-task response latencies. *Psychological Research, 70,* 484–493. http://dx.doi.org/10.1007/s00426-005-0011-9

Miller, J. (2017). Psychophysiological measurement of backward response activation in the prioritized processing paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 43,* 941–953. http://dx.doi.org/10.1037/xhp0000356

Miller, J., & Durst, M. (2014). "Just do it when you get a chance": The effects of a background task on primary task performance. *Perception & Psychophysics, 76,* 2560–2574. http://dx.doi.org/10.3758/s13414-014-0730-3

Miller, J., & Durst, M. (2015). A comparison of the psychological refractory period and prioritized processing paradigms: Can the response-selection bottleneck model explain them both? *Journal of Experimental Psychology: Human Perception and Performance, 41,* 1420–1441. http://dx.doi.org/10.1037/xhp0000103

Miller, J., & Reynolds, A. (2003). The locus of redundant-targets and nontargets effects: Evidence from the psychological refractory period paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 1126–1142. http://dx.doi.org/10.1037/0096-1523.29.6.1126

Miller, J., Ulrich, R., & Rolke, B. (2009). On the optimality of serial and parallel processing in the psychological refractory period paradigm: Effects of the distribution of stimulus onset asynchronies. *Cognitive Psychology, 58,* 273–310. http://dx.doi.org/10.1016/j.cogpsych.2006.08.003

Mittelstädt, V., & Miller, J. (2017). Separating limits on preparation versus online processing in multitasking paradigms: Evidence for resource models. *Journal of Experimental Psychology: Human Perception and Performance, 43,* 89–102. http://dx.doi.org/10.1037/xhp0000277

Paelecke, M., & Kunde, W. (2007). Action-effect codes in and before the central bottleneck: Evidence from the psychological refractory period paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 33,* 627–644. http://dx.doi.org/10.1037/0096-1523.33.3.627

Pashler, H. (1984). Processing stages in overlapping tasks: Evidence for a central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 358–377. http://dx.doi.org/10.1037/0096-1523.10.3.358

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin, 116,* 220–244. http://dx.doi.org/10.1037/0033-2909.116.2.220

Pfister, R., & Janczyk, M. (2013). Confidence intervals for two sample means: Calculation, interpretation, and a few simple rules. *Advances in Cognitive Psychology, 9,* 74–80. http://dx.doi.org/10.2478/v10053-008-0133-x

Renas, S., Durst, M., & Janczyk, M. (2017). Action effect features, but not anatomical features, determine the Backward Crosstalk Effect: Evidence from crossed-hands experiments. *Psychological Research*. Advance online publication. http://dx.doi.org/10.1007/s00426-017-0873-7

Röttger, E., & Haider, H. (2017). Investigating the characteristics of "not responding": Backward crosstalk in the PRP paradigm with forced vs. free no-go decisions. *Psychological Research, 81,* 596–610. http://dx.doi.org/10.1007/s00426-016-0772-3

Sasaki, K., Gemba, H., Nambu, A., & Matsuzaki, R. (1993). No-go activity in the frontal association cortex of human subjects. *Neuroscience Research, 18,* 249–252. http://dx.doi.org/10.1016/0168-0102(93)90062-U

Schubert, T., Fischer, R., & Stelzel, C. (2008). Response activation in overlapping tasks and the response-selection bottleneck. *Journal of Experimental Psychology: Human Perception and Performance, 34,* 376–397. http://dx.doi.org/10.1037/0096-1523.34.2.376

Schweickert, R. (1978). A critical path generalization of the additive factor method: Analysis of a Stroop task. *Journal of Mathematical Psychology, 18,* 105–139. http://dx.doi.org/10.1016/0022-2496(78)90059-7

Smith, M. C. (1967). The psychological refractory period as a function of performance of a first response. *The Quarterly Journal of Experimental Psychology, 19,* 350–352. http://dx.doi.org/10.1080/14640746708400114

Strobach, T., Liepelt, R., Pashler, H., Frensch, P. A., & Schubert, T. (2013). Effects of extensive dual-task practice on processing stages in simultaneous choice tasks. *Perception & Psychophysics, 75,* 900–920. http://dx.doi.org/10.3758/s13414-013-0451-z

Telford, C. W. (1931). The refractory phase of voluntary and associative responses. *Journal of Experimental Psychology, 14,* 1–36. http://dx.doi.org/10.1037/h0073262

Thomson, S. J., Danis, L. K., & Watter, S. (2015). PRP training shows Task1 response selection is the locus of the backward response compatibility effect. *Psychonomic Bulletin & Review, 22,* 212–218. http://dx.doi.org/10.3758/s13423-014-0660-z

Ulrich, R., Schröter, H., Leuthold, H., & Birngruber, T. (2015). Automatic and controlled stimulus processing in conflict tasks: Superimposed diffusion processes and delta functions. *Cognitive Psychology, 78,* 148–174. http://dx.doi.org/10.1016/j.cogpsych.2015.02.005

Van Selst, M., & Johnston, J. C. (1997). Dual-task interference when a response is not required. In M. G. Shafto & P. Langley (Eds.), *Proceedings of the nineteenth annual conference of the Cognitive Science Society* (pp. 787–792). Mahwah, NJ: Erlbaum.

Verbruggen, F., & Logan, G. D. (2008). Automatic and controlled response inhibition: Associative learning in the go/no-go and stop-signal paradigms. *Journal of Experimental Psychology: General, 137,* 649–672. http://dx.doi.org/10.1037/a0013170

Wagenmakers, E.-J. (2007). A practical solution to the pervasive problems of p values. *Psychonomic Bulletin & Review, 14,* 779–804. http://dx.doi.org/10.3758/bf03194105

Watter, S., & Logan, G. D. (2006). Parallel response selection in dual-task situations. *Perception & Psychophysics, 68,* 254–277. http://dx.doi.org/10.3758/BF03193674

Welford, A. T. (1952). The 'psychological refractory period' and the timing of high-speed performance—A review and a theory. *British Journal of Psychology General Section, 43,* 2–19. http://dx.doi.org/10.1111/j.2044-8295.1952.tb00322.x

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10.2 Study 2

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To prepare or not to prepare? When preparation of a response in Task 2 induces extra performance costs in Task 1.

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Abstract

In dual-tasking, the no-go backward crosstalk effect (BCE) means that processing of Task 1 takes longer when Task 2 does not require a response (no-go-trial) than when it requires a response (go-trial). Thus, contrary to the usual observation, giving two successive responses counterintuitively reduces instead of increases performance costs for Task 1. Results from recent studies are in line with the notion that the no-go BCE reflects response inhibition, which is required to overcome an already prepared go response in Task 2 but which also spills over to motor execution in Task 1. No direct test of this hypothesis, however, has been carried out so far and hence the present study was designed to fill this gap. The result of this study with n = 48 participants revealed that a no-go Task 2 impeded Task 1 performance when preparation of the Task 2 response was encouraged, but facilitated Task 1 performance when preparation of the Task 2 response was not encouraged.

Keywords: dual-task, backward crosstalk, go/no-go task, response preparation

Response preparation determines the direction of no-go Backward Crosstalk

Performing movements in two motor tasks simultaneously, that is dual-tasking, can be very difficult, and often comes at the cost of performing one or both movements slower and/or producing more errors. Just imagine learning to play drums where you have to simultaneously coordinate contrary movements of both arms and feet. As most dual-tasking research and popular opinions nowadays focus on the difficulties of dual-tasking, situations in which negative consequences are *reduced* when two instead of only one movement are carried out are often overlooked. However, this happens in *no-go backward crosstalk* experiments.

Miller (2006) was the first to combine a manual two-choice Task 1 with a go/no-go Task 2 (see Donders, 1969). For example, in his Experiment 1, participants were instructed to respond to the identity of a letter by pressing a key with their left index or middle finger in Task 1, and to respond to the pitch of a tone by pressing a key with their right index finger (go-trials) or by withholding the response (no-go-trials) in Task 2. Task 1 RTs were shorter when Task 2 required a response relative to when it did not. This *no-go backward crosstalk effect* (no-go BCE) is an example of how dual-task costs are actually reduced when two motor tasks have to be carried out (see also Ko & Miller, 2014; Miller & Durst, 2014, 2015), even though the addition of a second task certainly impedes performance of the first task overall (i.e., general dual-task costs are present).

The most often invoked explanation for the no-go BCE is that inhibition is required to withhold an already prepared Task 2 response in no-go-trials, whereby some inhibition spills over to Task 1 and thus prolongs RT1s in no-go-trials (Janczyk & Huestegge, 2017; Miller, 2006). In addition, recent results from a mental chronometry study (Durst & Janczyk, 2018) also suggest that indeed motor execution in Task 1 is prolonged in Task 2 no-go-trials, thus lending additional support for the preparation hypothesis. As an alternative explanation, Röttger and Haider (2017) suggested that the no-go BCE is based on automatic response feature activation. For instance, such response features could be response effects which seem to play an important role in the selection of no-go responses as well (Kühn, Elsner, Prinz, & Brass, 2009). In this sense, the sensory consequence of a go and no-go response would be incompatible, which could impair Task 1 performance in no-go-trials. Alternatively, the incompatibility of abstract "go-representations" versus "no-go representations" could impair Task 1 performance. Importantly, according to this hypothesis, mere perception of a no-go stimulus in Task 2 should automatically activate the (incompatible) no-go representation and thereby impair performance of Task 1 (which always involves a go representation). In sum, and in contrast to the above mentioned preparation hypothesis, the no-go BCE would then emerge entirely independent from the preparatory status of the Task 2 response.

Even though the larger part of evidence indirectly supports the preparation hypothesis, a direct test of the competing explanations still lacks. The present study fills this gap. To this end, a two-choice Task 1 was combined with a choice/no-go Task 2, which either required one of two go-responses or to withhold the response (no-go-response). The critical manipulation was that preparation of a Task 2 go-response was either encouraged or not by varying the frequency of the Task 2 go-stimuli, keeping everything else equivalent. More specifically, in one half of the blocks, both go-stimuli occurred equally often (neutral blocks). Thus, participants would be less encouraged to prepare one or the other response in advance and consequently no or even a reversed no-go BCE was expected, because there was nothing to inhibit in case of a no-go-stimulus (see also Janczyk & Huestegge, 2017, for this observation). In the other half of blocks, one go-stimulus occurred in 90% of the go-trials (biased blocks), thereby encouraging preparation of the more often required Task 2 response. In this case, the preparation hypothesis predicts that the no-go BCE should re-emerge in these biased blocks. Although previous research has supported the view that the no-go BCE has its locus in the motor stage of Task 1 (Durst & Janczyk, 2018), the role of preparation in Task 2 (and the required inhibition) has not been addressed directly so far. Yet, evidence for the preparation hypothesis would not only help to better understand the no-go BCE as such, but also to further delineate it from compatibility-based BCEs (Hommel, 1998). These latter BCEs occur when both tasks overlap, for example, in their spatial response features, are caused by automatic response feature activation in Task 2, and have their locus during Task 1 response selection instead of motor execution (see Janczyk, Renas, & Durst, 2018; and Durst & Janczyk, 2019, for a direct comparison of both kinds of BCEs).

Method

Participants. Forty-eight people (28 female) from the Tübingen (Germany) area, aged 19 to 64 years (*M* = 23.21 years, *SD* = 6.56), participated for monetary compensation (8€) or course credit. All participants provided written informed consent before the experiment and reported normal or corrected-to-normal vision.

According to Röttger and Haider (2017, p. 602) their Experiment 1 and Miller's (2006) Experiment 1 exhibited large effect sizes ($\boldsymbol{\eta}_\mathbf{p}^\mathbf{2} > .5$). The effect of interest in our experiments is a 2×2 interaction of two repeated-measures which can be broken down to a (paired) *t*-test, and we (conservatively) assume a medium effect size of $d_z = 0.5$ (Cohen, 1988). Power analysis using the function `power.t.test()` of the R-software yielded a required sample size of $n \approx 44$ participants to achieve $1\text{-}\beta = .90$, with $\alpha = .05$.

Apparatus and Stimuli. A standard PC was used for stimulus presentation and response collection. Stimuli and instructions were presented on a 17-inch CRT monitor. Stimuli were the letters 'X' and 'O' colored in red, green, and blue and presented in the center of an otherwise black screen. The identity of the letter served as Stimulus 1 (S1), the color of the letter served as Stimulus 2 (S2). Responses to S1 were given via a manual key-press of the left index or middle finger (R1). Responses to S2 were given via a manual key-press of the right index or middle finger, or by withholding the response (R2). Custom made keys were used to collect all responses and two keys each were placed to the left and to the right of the participant.

***Task and Procedure*.** The trial structure is illustrated in Figure 1. Task 1 was to respond to S1 with a manual key-press of the left index or middle finger, and Task 2 was either to respond to S2 (go-trial) with an index or middle finger key-press of the right hand or to withhold the response (no-go-trial).

Each trial started with a white fixation cross (250 ms), followed by a blank screen (250 ms). Subsequently, the colored letter was presented at the center of the screen for a maximum of 4,000 ms or until R1 and R2 were registered. The next trial started after an inter-trial interval (ITI) of 1,000 ms. In case of wrong responses or general errors (no response within 4,000 ms following stimulus onset, responses in the wrong order, response with a wrong key, and so on), specific error feedback was provided for 1,000 ms before the ITI.

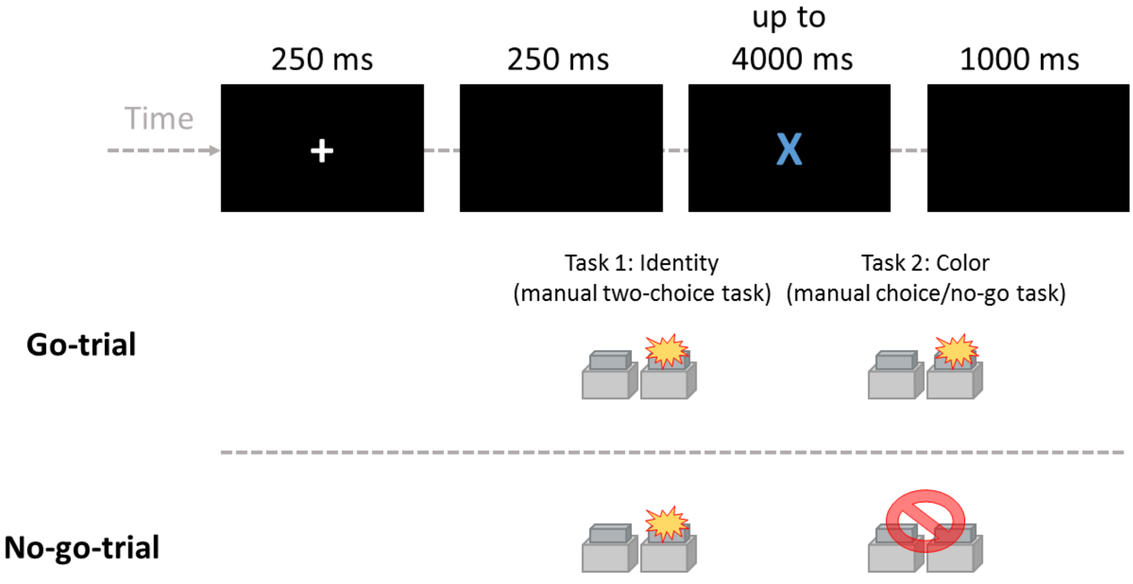

Figure 1. Graphical illustration of the trial structure for go- and no-go-trials. Participants first responded to the identity of the letter in a manual two-choice task with the left hand and subsequently to the color of the letter in a manual choice/no-go task with the right hand. In this particular example, an X calls for a response with the left index-finger in Task 1. Depending on the stimulus-response mapping the color blue either calls for a response with the right middle-finger (go-trial), or for withholding any response in Task 2.

Participants first performed a short familiarization block of 20 randomly drawn trials, which was followed by eight experimental blocks of 60 trials each. All trials were presented in a random order. Throughout the experiment, the S2 associated with the no-go-response occurred in one third of the trials (no-go trials), while an S2 associated with a go-response of the right hand occurred in the remaining two thirds of all trials (go-trials). In neutral blocks, both S2 associated with go responses occurred equally often (i.e., 20 times), whereas in the biased blocks, one S2 associated with either the right index or middle finger response occurred in 90% of all go-trials (i.e., 36 times).

Participants received written instructions that informed them about the frequency of the two possible go-S2s in the upcoming blocks. After the first four blocks, participants were told that the instructions would change in the remaining blocks and therefore to contact the experimenter. Before the remaining blocks were started, the experimenter made sure that participants understood the altered instructions concerning the new frequency of the two go-S2s. In general, the instructions emphasized speed and accuracy, and participants were asked to give R1 and R2 successively in fixed order, and to wait until the trial ended in case of a no-go-trial. The stimulus-response mapping of all tasks, as well as the order of blocks (neutral vs. biased blocks first), and the S2 that occurred in 90% of go-trials in biased blocks were counterbalanced across participants.

Design and Analysis. Trials in which a response in Task 2 was required (i.e., a right index or middle finger response) were considered go-trials, whereas trials in which a response in Task 2 was to be withheld were considered no-go-trials. Data from the practice block were excluded from analyses. For the analysis of RTs, trials deviating more than 2.5 standard deviations from the individual cell means were considered outliers and excluded from analyses. Error rates in both tasks (ER1 and ER2) were arcsine transformed for statistical analyses, but raw ERs are reported as descriptive statistics. For Task 1, mean correct RT1s and ER1 were submitted to 2 × 2 Analyses of Variance (ANOVA) with trial type (go vs. no-go) and block type (neutral vs. biased) as repeated measures. For Task 2, mean correct RT2s were submitted to an ANOVA with Response 2 frequency[1] (neutral vs. frequent vs. less frequent) as a repeated measure. For ER2 an ANOVA with Response 2 frequency as a repeated measure for errors in go-trials (a response was withheld when it was actually required) and an ANOVA with block type for errors in no-go-trials (a response was given when it should be withheld) were calculated separately.

Results

Mean RT1s are visualized in Figure 2 (see also Table 1 for mean RT1s and ER1s), and all mean RT2s and ER2s are summarized in Table 2. For RT1, 2.73% of all trials were considered outliers and for RT2, 1.75% of all trials were considered outliers.

Task 1. The ANOVA yielded no significant main effect of trial type, $F(1,47) = 0.48$, $p = .492$, $\eta_p^2 = .01$. The main effect of block type was significant, with RT1s being on average 70 ms longer in neutral (712 ms) relative to biased blocks (642 ms), $F(1,47) = 28.37$, $p < .001$, $\eta_p^2 = .38$. Most importantly, the interaction was significant, $F(1,47) = 69.57$, $p < .001$, $\eta_p^2 = .60$. The no-go BCE was present in biased blocks (63 ms), $t(47) = 5.62$, $p < .001$, $d = 0.81$, and in neutral blocks, it was inverted (-50 ms), $t(47) = -4.18$, $p < .001$, $d = -0.60$. Error rates were very low, but the analysis for ER1 revealed a significant main effect of trial type, with on average 1.30% more errors for go- (2.54%) relative to no-go-trials (1.24%), $F(1,47) = 53.25$, $p < .001$, $\eta_p^2 = .53$. Neither the main effect of block type, $F(1,47) = 0.01$, $p = .915$, $\eta_p^2 < .01$, nor the interaction were significant, $F(1,47) = 0.07$, $p = .798$, $\eta_p^2 < .01$.[2]

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[1] This factor refers to the actual experimental manipulation. Note though that the critical assumption is that a frequent Task 2 response is prepared.

[2] Note that the higher ER1 for go- relative to no-go-trials in biased blocks opposes the results pattern for RT1s, which suggests that a speed-accuracy tradeoff (SAT, see, Liesefeld & Janczyk, 2018) was present. This could potentially complicate the interpretation of the present results. An analysis of the potential influence of the SAT can be found in the appendix. The critical interaction observed in RT1 was not compromised by an SAT.

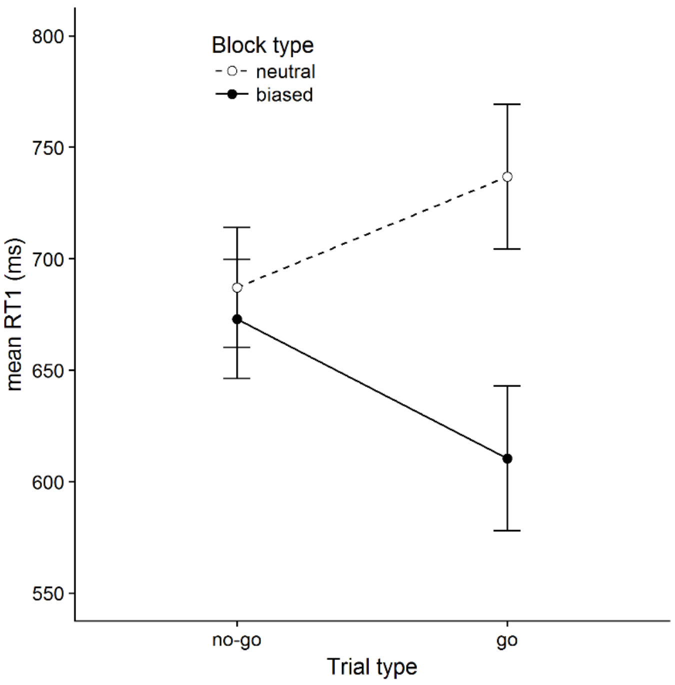

Figure 2. Mean RTs of Task 1 (RT1) as a function of trial type (no-go vs. go) and block type (neutral vs. biased). Error bars are 95% within-subject confidence intervals for the difference between block type (see Pfister & Janczyk, 2013).

Table 1. Mean RT1s (in ms) and Error Rates (ER1, in %) for Task 1 as a function of trial type and block type.

		Trial type	
	Block type	No-go	Go[3]
RT1	Neutral	687	737
	Biased	673	610
ER1	Neutral	1.30	2.49
	Biased	1.18	2.60

Task 2. The analysis for RT2 revealed a significant main effect of Response 2 frequency, $F(2,94) = 64.75$, $p < .001$, $\eta_p^2 = .58$. On average the longest RT2s were observed for less frequent responses (1,105 ms), with intermediate RT2s for neutral blocks (982 ms), and shortest RT2s for frequent responses (783 ms). All pairwise comparisons were significant, all ts ≥ 12.47, all ps $\leq .001$. This suggests that participants prepared the more likely R2 alternative in advance.

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[3] Mean RT1 and ER1 for biased blocks were also calculated separately for frequent and less frequent go-responses in Task 2. RT1s for frequent responses were 587 ms and mean RT1s for less frequent responses were 856 ms. ER1 for frequent responses was 2.39% and ER1 for less frequent responses was 4.51%.

The ANOVA for ER2 in go-trials yielded a significant main effect of Response 2 frequency, *F*(2,94) = 21.25, *p* < .001, η_p^2 = .31. On average ER2 for go-trials in neutral blocks (4.64%) was larger relative to frequent responses (1.68%), *t*(47) = -7.83, *p* < .001, *d* = -1.13, and relative to less frequent responses (3.05%), *t*(47) = -5.29, *p* < .001, *d* = -0.76. However, ER2 neither differed between frequent and less frequent responses in go-trials, *t*(47) = 0.24, *p* = .810, *d* = 0.03, nor between no-go-trials of neutral and biased blocks, *F*(1,47) = 1.35, *p* = .251, η_p^2 = .03.

Table 2. Mean RT2s (in ms) and Error Rates (ER2, in %) for Task 2 as a function of trial type and block type (Response 2 frequency).

		Trial type	
	Block type (Response 2 frequency)	No-go	Go
RT2	Neutral		982
	Biased (frequent)		783
	Biased (less frequent)		1105
ER2	Neutral	0.26	4.64
	Biased (frequent)	1.15	1.68
	Biased (less frequent)		3.05

Note, that in no-go-trials of biased blocks no distinction between frequent and less frequent responses in Task 2 can be made. Thus, only one mean ER2 for no-go-trials in biased blocks can be reported.

Discussion

Usually, giving two temporally overlapping responses in two different tasks results in worse performance in one or both of the tasks – that is, most often prolonged RTs – in comparison with their isolated application. Such dual-task costs are a common observation and only few exceptions were reported (see Janczyk, Pfister, Wallmeier, & Kunde, 2014), and thus a possible beneficial aspect of dual-tasking is only rarely considered (but see, e.g., Reissland & Manzey, 2016). Yet, there are situations in which giving two temporally overlapping responses can actually be at least less detrimental compared to giving only one response. Such a counterintuitive effect has been observed when Task 2 requires a response (go-trial) compared to when Task 2 demands no response (no-go-trial) (e.g., Durst & Janczyk, 2018; Miller, 2006). Presumably, this so-called no-go BCE arises from the inhibition of an already prepared Task 2 response, spilling over to Task 1, and impeding motor execution in this task (but see Röttger & Haider, 2017, for an alternative explanation). To directly test this preparation hypothesis, we compared performance in two different blocks, where Task 2 was always a choice/no-go task: In neutral blocks, preparation of a particular go-response was not encouraged, but in biased blocks, one response was required more frequently than the other, thus encouraging advance preparation of this particular response.

Task 1 performance in no-go-trials suffers only when Task 2 response preparation is encouraged. The present results are straightforward. First, RT2s for frequent responses were shorter than those for less frequent responses, supporting the idea that participants indeed prepared for the more likely response alternative. Second, in neutral blocks, RT1 was shorter when Task 2 was a no-go-trial, replicating results reported by Janczyk and Huestegge (2017). Most important, this pattern was reversed in biased blocks, thus the no-go BCE re-emerged when preparation of a Task 2 response was encouraged. This result supports the preparation hypothesis and is also in line with the assumption that the inhibition of an already prepared response is the mechanism that underlies the no-go BCE. In a recent mental-chronometry study, Durst and Janczyk (2018) obtained further evidence that the no-go BCE arises during motor execution (i.e., the *locus* of the no-go BCE) of Task 1 when it temporally overlaps with the central stage (i.e., the *source* of the no-go BCE) of Task 2 (for an illustration see, Durst & Janczyk, 2018, Figure 1d). They suggested (motor) inhibition as the controlled process occurring in the central stage of Task 2 processing, causing the no-go BCE at the level of motor execution of Task 1. Note that the present results are not in line with an alternative explanation for the no-go BCE that was advanced by Röttger and Haider (2017). According to this account, a no-go-trial automatically implies the activation of, for example, a no-go tag or the absence of sensory feedback when not responding – features that are on a more abstract level incompatible with Task 1 features. Thus, if this explanation were true, the same no-go BCE would have been expected regardless of block type.

Possible objections and limitations. Although the main results are straightforward, some aspects are worth discussing. One observation that appears not to be in line with the assumed inhibition in biased blocks is that RT1s for no-go-trials are similar in neutral and biased blocks. At first glance, one would have expected longer no-go RT1s in biased compared with neutral blocks instead. We concur, but we believe that several explanations for this are conceivable. Due to the block-wise application, we cannot exclude further differences that either decreased RT1s in biased blocks or increased RT1s in neutral blocks (or both), thereby obscuring the expected difference for no-go-trials. For example, the possibility of preparation in biased blocks may have led to a better preparation in general, which decreased RT1s in biased blocks. Further, as RT2s were also longer for neutral than for biased blocks, even a small portion of grouped responses in neutral blocks may have increased RT1s accordingly.

A second objection concerns the nature of the neutral blocks in our experiment. One important advantage of our design is that – except for the distribution of the go-response frequencies – both blocks are comparable. However, one might suggest that in neutral blocks no inhibition occurred in no-go-trials, because the two-choice/no-go task was more similar to a three-choice task. In this case, left versus right response code overlap may have induced a compatibility-based BCE in go-trials that may have prolonged RT1 in neutral blocks. It is, however, unclear whether such code overlap necessarily leads to interference. Rather, in case of two compatible responses, facilitation is likely as well. Further, an exploratory post-hoc analysis revealed that such a compatibility-based BCE was not evident in the data, $t(47) = -1.40$, $p = .168$, and numerically even inversed.

Relations to other phenomena. The present results can also be related to other phenomena. For example, a reduction in dual-task costs in Task 1 was also reported when saccadic eye movements were required in Task 2 as compared to keeping the eye fixated at the screen center (Huestegge & Koch, 2014; see also Raettig & Huestegge, 2018). These studies assumed that a saccadic eye movement toward a peripheral target occurs rather automatically, and thus inhibition is needed to keep the eye fixated at the screen center. Again then, performing only one motor response is harder than performing two responses in this setup as well and inhibition appears to be the underlying mechanism for this.

Our manipulation of stimulus and response frequency conceivably renders the less frequent stimuli unexpected. Unexpected events, in turn, are also known for slowing ongoing responses (Wessel & Aaron, 2013; Wessel, 2018), and this might have affected RT1s as well. In fact, in a post-hoc exploration, RT1s were slower for less frequent Task 2 responses than for the frequent Task 2 responses. However, given that RT2s were slower as well, it is difficult to separate effects of unexpectedness from other possible sources with the present design. For example, RT1s may as well have been prolonged via response grouping (see Ulrich & Miller, 2008) or because less frequent responses impose larger dual-task costs in general. Future research should try to separate unexpectedness from other sources to identify a possible unique contribution.

The present results further support the assumption that the no-go BCE is caused by inhibition of a prepared Task 2 response. As such it seems important to clearly distinguish the no-go BCE from other types of BCEs, which have different causes. The most-well known other type are compatibility-based BCEs, which are likely caused by automatic response feature activation occurring in Task 2 (Hommel, 1998; Lien & Proctor, 2000; Janczyk, Pfister, Hommel, & Kunde, 2014; Janczyk et al., 2018;Oriet, Tombu, & Jolicoeur, 2005; Logan & Schulkind, 2000; Logan & Delheimer, 2001; Renas, Durst, & Janczyk, 2018; Schubert, Fischer, & Stelzel, 2008; Watter & Logan, 2006; see Durst & Janczyk, 2019, for a direct comparison). To allow for a more precise distinction of backward crosstalk phenomena, future studies should investigate to what extent the no-go BCE differs from still other types of BCEs, which seem to be based on motor processes in Task 1, Task 2, or even both tasks (Miller & Alderton, 2006; Ruiz Fernández & Ulrich, 2010).

Conclusion. Motivated by the different suggestions advanced in the previous literature (Durst & Janczyk, 2018; Janczyk & Huestegge, 2017; Miller, 2006; Röttger & Haider, 2017), the present study provides a direct test that preparation of a Task 2 response and its inhibition in no-go-trials is the reason for performance decrements in Task 1, when Task 2 is a no-go task – a phenomenon known as the no-go BCE. More generally, the present results support the view that reduced preparation for Task 2 can reduce performance decrements in Task 1. Therefore, performing two motor responses at the same time can not only produce the usual observation of dual-task costs, but can under certain circumstances reduce these costs.

Appendix

Speed accuracy tradeoff (SAT). The higher ER1 for go- relative to no-go-trials in biased blocks opposes the results pattern for RT1s, where RT1s were shorter in go- relative to no-go-trials. This suggests that a speed-accuracy tradeoff (SAT) was present, which could complicate the interpretation of the present results; although the descriptive difference for ER1 was small in general.

To investigate whether the SAT modulated the pattern of results obtained for RT1, the method of Janczyk (2016) was adopted. To this end, no-go BCEs for RT1 and ER1 were calculated for each participant. If the signs of both no-go BCEs did not match, an SAT for the respective participant was indicated. RT1 data were then submitted to a mixed ANOVA with trial type and block type as repeated measures plus the additional between-subjects factor SAT.

The main effect of SAT was not significant, $F(1,46) = 1.25, p = .270, \eta_p^2 = .03$. However, the interaction of trial type and SAT was significant, $F(1,46) = 6.38$, $p = .015$, $\eta_p^2 = .12$. The interaction of block type and SAT was not significant, $F(1,46) = 0.47$, p = .498, $\eta_p^2 = .01$. Most crucially, the interaction of trial type and block type was significant, $F(1,46) = 64.20, p < .001$, $\eta_p^2 = .58$, but the interaction of SAT, trial type, and block type was not significant, $F(1,46) = 0.01, p = .931, \eta_p^2 < .01$. Additional separate analyses for participants with and without an SAT yielded qualitatively similar results.

Taken together, the results of the SAT analysis indicate that the SAT did *not* modulate the crucial interaction of trial type and block type, as the three-way interaction was not significant. This renders the interpretation of the present results unproblematic.

References

Donders, F. C. (1969). On the speed of mental processes. *Acta Psychologica, 30,* 412-431.

Durst, M., & Janczyk, M. (2018). The motor locus of no-go backward crosstalk. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 44,* 1931-1946.

Durst, M., & Janczyk, M. (2019). Two types of backward crosstalk: Sequential modulations and evidence from the diffusion model. *Acta Psychologica, 193,* 132-152. doi:https://doi.org/10.1016/j.actpsy.2018.11.013

Hommel, B. (1998). Automatic stimulus–response translation in dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 1368-1384.

Huestegge, L., & Koch, I. (2014). When two actions are easier than one: How inhibitory control demands affect response processing. *Acta Psychologica, 151,* 230-236.

Huestegge, L., Pieczykolan, A., & Janczyk, M. (2018). Backward crosstalk and the role of dimensional overlap within and between tasks. *Acta Psychologica, 188,* 139-147.

Janczyk, M. (2016). Sequential modulation of backward crosstalk and task-shielding in dual-tasking. *Journal of Experimental Psychology: Human Perception and Performance, 42,* 631-647.

Janczyk, M., & Huestegge, L. (2017). Effects of a no-go Task 2 on Task 1 performance in dual-tasking: From benefits to costs. *Attention, Perception, & Psychophysics, 79,* 796-806.

Janczyk, M., Pfister, R., Hommel, B., & Kunde, W. (2014). Who is talking in backward crosstalk? Disentangling response-from goal-conflict in dual-task performance. *Cognition, 132,* 30-43.

Janczyk, M., Pfister, R., Wallmeier, G., & Kunde, W. (2014). Exceptions to the PRP effect? A comparison of prepared and unconditioned reflexes. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*, 776.

Janczyk, M., Renas, S., & Durst, M. (2018). Identifying the locus of compatibility-based backward crosstalk: Evidence from an extended PRP paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 44,* 261-276.

Ko, Y.-T., & Miller, J. (2014). Locus of backward crosstalk effects on task 1 in a psychological refractory period task. *Experimental Psychology, 61,* 30-37.

Kühn, S., Elsner, B., Prinz, W., & Brass, M. (2009). Busy doing nothing: Evidence for nonaction—effect binding. *Psychonomic Bulletin & Review, 16,* 542–549.

Lien, M.-C., & Proctor, R. W. (2000). Multiple spatial correspondence effects on dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 1260-1280.

Liesefeld, H. R., & Janczyk, M. (2018). Combining speed and accuracy to control for speed-accuracy trade-offs(?). *Behavior Research Methods,* 1-21. doi:10.3758/s13428-018-1076-x

Logan, G. D., & Delheimer, J. A. (2001). Parallel memory retrieval in dual-task situations: II. Episodic memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27,* 668.

Logan, G. D., & Schulkind, M. D. (2000). Parallel memory retrieval in dual-task situations: I. Semantic memory. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 1072.

Miller, J. (2006). Backward crosstalk effects in psychological refractory period paradigms: Effects of second-task response types on first-task response latencies. *Psychological Research, 70,* 484-493.

Miller, J., & Alderton, M. (2006). Backward response-level crosstalk in the psychological refractory period paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 32,* 149.

Miller, J., & Durst, M. (2014). “Just do it when you get a chance”: the effects of a background task on primary task performance. *Attention, Perception, & Psychophysics, 76,* 2560-2574.

Miller, J., & Durst, M. (2015). A comparison of the psychological refractory period and prioritized processing paradigms: Can the response-selection bottleneck model explain them both? *Journal of Experimental Psychology: Human Perception and Performance, 41,* 1420-1441.

Oriet, C., Tombu, M., & Jolicoeur, P. (2005). Symbolic distance affects two processing loci in the number comparison task. *Memory & Cognition, 33,* 913-926.

Pfister, R., & Janczyk, M. (2013). Confidence intervals for two sample means: Calculation, interpretation, and a few simple rules. *Advances in Cognitive Psychology, 9,* 74-80.

Raettig, T., & Huestegge, L. (2018). The hard work of doing nothing: Accounting for inhibitory costs during multiple action control. *Attention, Perception, & Psychophysics, 80,* 1660-1666.

Reissland, J., & Manzey, D. (2016). Serial or overlapping processing in multitasking as individual preference: Effects of stimulus preview on task switching and concurrent dual-task performance. *Acta Psychologica, 168,* 27-40.

Renas, S., Durst, M., & Janczyk, M. (2018). Action effect features, but not anatomical features, determine the backward crosstalk effect: Evidence from crossed-hands experiments. *Psychological Research, 82,* 970-980.

Röttger, E., & Haider, H. (2017). Investigating the characteristics of “not responding”: backward crosstalk in the PRP paradigm with forced vs. free no-go decisions. *Psychological Research, 81,* 596-610.

Ruiz Fernández, S., & Ulrich, R. (2010). Late backward effects in the refractory period paradigm: effects of Task 2 execution on Task 1 performance. *Psychological Research, 74,* 378-387.

Schubert, T., Fischer, R., & Stelzel, C. (2008). Response activation in overlapping tasks and the response-selection bottleneck. *Journal of Experimental Psychology: Human Perception and Performance, 34,* 376-397.

Watter, S., & Logan, G. D. (2006). Parallel response selection in dual-task situations. *Perception & Psychophysics, 68,* 254-277.

Wessel, J. R. (2018). Surprise: A more realistic framework for studying action stopping? *Trends in Cognitive Sciences, 22,* 741-744.

Wessel, J. R., & Aron, A. R. (2013). Unexpected events induce motor slowing via a brain mechanism for action-stopping with global suppressive effects. *The Journal of Neuroscience, 33,* 18481-18491.

10.3 Study 3

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Two types of backward crosstalk: Sequential modulations and evidence from the diffusion model

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ABSTRACT

In multitasking, the backward crosstalk effect (BCE) means that Task 1 performance is influenced by characteristics of Task 2. For example, (1) RT1 is shorter when the two responses are given on the same (compatible trial) compared with opposite sides (incompatible conflict-trial; compatibility-based BCE), and (2) RT1 is longer when Task 2 is a no-go relative to a go task (no-go BCE). We investigated the impact of recently experienced trial and conflict history on the size of such BCEs. Similar to the Gratton effect in standard conflict tasks, clear sequential modulations were observed for the two kinds of BCEs, which were present following (1) compatible trials and (2) go-trials and inverted following (1) incompatible and (2) no-go trials. Furthermore, recent evidence from mental chronometry studies suggests that the compatibility-based BCE is located inside the response selection stage, while the no-go-based BCE arises in motor execution. Against this background, a diffusion model analysis was carried out to reveal the reason(s) for the sequential modulations. As expected, for the compatibility-based BCE, changes in drift rate explain the sequential modulations, but for the no-go BCE changes in non-decision time are important. The present results indicate that both BCEs not only differ fundamentally in their underlying processes, but also in the way cognitive control is adjusted.

1. Introduction

At first glance, it seems as if humans are able to carry out multiple tasks at a time without any problems. However, extensive research in cognitive psychology teaches us the opposite: Performance declines under a wide range of seemingly very easy laboratory tasks (e.g., Pashler, Johnston, & Ruthruff, 2001) and also in more applied settings (Levy & Pashler, 2008; Strayer & Drews, 2004, 2007). Today, it is still hotly debated whether humans are even able to process two or more tasks in parallel or whether human cognition is limited to processing only one task at a time in a strictly serial manner.

The widespread and well-accepted response selection (RS) bottleneck model (Pashler, 1984, 1994; Welford, 1952) assumes that only one task at a time can get access to the RS stage. Thus, while RS in Task 1 is ongoing, that of Task 2 must wait until RS is available again. Accordingly, response times (RTs) for Task 2 are prolonged by this idle time of waiting (e.g., Pashler, 1994; for possible exceptions, see Janczyk, Pfister, Wallmeier, & Kunde, 2014). Others have suggested that processing of different tasks requires the same limited resource, which can be shared between tasks to allow for parallel—but less efficient—processing (Navon & Miller, 2002; Tombu & Jolicœur, 2003). Converging evidence for this view was put forward in the recent past (Mittelstädt & Miller, 2017; for a review, see Fischer & Plessow, 2015). One frequently reported observation that was taken to indicate parallel processing in dual-tasking is that characteristics of Task 2 can already influence performance in Task 1—so-called *backward crosstalk effects* (BCEs).

The structure of the present paper is as follows. We will first introduce two types of BCEs that we suggest are qualitatively different, although it is important to note that this is yet controversial in the literature. We then turn to sequential modulations of these BCEs, that is, the influence of a previous Trial $n-1$ on performance in the current Trial n. To substantiate our assumption about the clear distinction of both BCEs, we then argue that the reasons for the sequential modulations—and thus the mechanisms adjusting cognitive control—in both BCEs should differ. To demonstrate that, we will reason that the mechanisms adjusting cognitive control in both BCEs can be mapped to different parameters of the diffusion model (Ratcliff, 1978). This is followed by a brief sketch of the diffusion model, before we then present the particular predictions for our experiment.

1.1. Two types of the BCE

The recent literature has documented several examples of BCEs, and our own research strongly suggests that several types of BCEs must be

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distinguished based on (1) the particular stage of Task 2 that causes the BCE (henceforth the *source*) and (2) the stage of Task 1 that is affected from this influence (henceforth the *locus* of the BCE). We here focus on the two types that have attracted most of the respective research so far, namely the compatibility-based BCE (Hommel, 1998) and the no-go BCE (Miller, 2006).

The first experiment on the *compatibility-based BCE* was reported by Hommel (1998). In Experiment 1, he presented participants with colored letters and instructed them to respond to the color of the letter with a left vs. right manual keypress, and to the identity of the letter with a vocal "left" vs. "right" utterance. Task 1 RTs (RT1s) were shorter for trials in which both responses were spatially compatible (e.g., a left keypress and a "left" utterance) compared to trials in which both responses were spatially incompatible (e.g., a left keypress and a "right" utterance). Thus, dimensional overlap between both tasks and the compatibility of task features (i.e., stimuli and/or responses) influenced Task 1 performance. Similar results have been reported in many other studies (Ellenbogen & Meiran, 2008; Hommel & Eglau, 2002; Janczyk, Pfister, Hommel, & Kunde, 2014; Lien & Proctor, 2000; Naefgen, Caissie, & Janczyk, 2017; Schubert, Fischer, & Stelzel, 2008; Watter & Logan, 2006). Such observations imply that at least some Task 2 RS-related processing must have proceeded in parallel to Task 1 RS. To align such results with the RS bottleneck model, it was suggested that a parallel-processing stage of response activation (RA) runs prior to RS and is where crosstalk between tasks can occur (Hommel, 1998; Lien & Proctor, 2002).

To clarify the underlying mechanisms of the compatibility-based BCE we (Janczyk, Renas, & Durst, 2018) recently investigated the locus of the compatibility-based BCE by applying the well-established locus of slack and effect propagation logic (for introductions, please see Janczyk, 2013, 2017; Kunde, Pfister, & Janczyk, 2012; Miller & Reynolds, 2003; Schweickert, 1978; and others) in a series of experiments using an extended Psychological Refractory Period (PRP) paradigm with three subsequent tasks. The results provided strong evidence for a locus inside Task 1 RS. As the source, we suggested automatic RA, which occurs if Task 2 does not gain direct access to the response selection stage (for a similar conclusion from a training study see, Thomson, Danis, & Watter, 2015; for evidence from the LRP, see Lien, Ruthruff, Hsieh, & Yu, 2007; Miller, 2017). In more detail, we suggested that automatic response feature activation from Task 2 adds to the evidence accumulated in Task 1 response selection (see Ulrich, Schröter, Leuthold, & Birngruber, 2015). Thereby, RT1s become shortened in compatible and prolonged in incompatible trials, in a similar way as flankers affect performance in an Eriksen flanker task (Eriksen & Eriksen, 1974). This is illustrated in Fig. 1a.

The *no-go BCE* was first reported by Miller (2006), who observed a BCE when a manual-choice Task 1 was combined with a go/no-go Task 2 (see Donders, 1969). In the latter task, participants responded with a keypress of their right index finger in go trials, and withheld this response in no-go trials. Miller observed shorter RT1s for go relative to no-go trials (see also Ko & Miller, 2014; Miller & Durst, 2014, 2015; Röttger & Haider, 2017).

One explanation for the no-go BCE is that the necessity to inhibit the already prepared Task 2 response spills over to Task 1 motor execution and thus prolongs RT1 in no-go trials (Janczyk & Huestegge, 2017; Miller, 2006). As an alternative explanation, it was suggested that the "go representation" of Task 1 conflicts with the "no-go representation" of Task 2, which causes the no-go BCE via automatic response feature activation, similar to what was suggested for the compatibility-based BCE (Röttger & Haider, 2017). However, a recent study applying the locus of slack and a modified effect propagation logic to the no-go BCE supported the inhibition hypothesis (Durst & Janczyk, 2018). The results indicated that Task 1 motor stage is the locus and that the source is the inhibition resulting from Task 2 RS. This is illustrated in Fig. 1b.

In sum, it appears as if both BCEs are based on fundamentally different cognitive processes and should, thus, be classified as *two different types of BCEs*. Notably, both types are usually assessed for the current trial only. However, the previous trial's characteristics also affect the size of at least the compatibility-based BCE, as will be explained in the next section. To allow for a more fine-grained assessment of the assumed distinction of both types of BCEs, the present study also considers the influence of the previous trial for both types of BCEs and directly addresses the underlying reasons for such sequential modulations.

1.2. *Sequential modulation of backward crosstalk effects*

A common observation in conflict tasks like, for instance, the Eriksen flanker task (Eriksen & Eriksen, 1974) is that the congruency effect in the present Trial *n* is larger if the preceding Trial $n-1$ was congruent relative to incongruent (Gratton, Coles, & Donchin, 1992). Similar observations have been reported for other conflict tasks as well (Simon: Praamstra, Kleine, & Schnitzler, 1999; see also Janczyk & Leuthold, 2018; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002; Wühr, 2004; Stroop: Kerns et al., 2004; Notebaert, Gevers, Verbruggen, & Liefooghe, 2006). Such *sequential modulations* (sometimes referred to as the *Gratton effect*) have been taken as evidence for rapidly ongoing adaptation to just experienced (response) conflict (for a review, see Egner, 2007). More precisely, the conflict monitoring hypothesis (Botvinick, Braver, Barch, Carter, & Cohen, 2001) suggests that registering conflict in a trial leads to optimized task processing in the subsequent trial, for example, by increasing processing of the task relevant stimulus.

In a very similar way, the size of the compatibility-based BCE is affected by the previous trial's compatibility, that is, this BCE is present only following compatible trials but absent (and sometimes even reversed) following incompatible trials (Janczyk, 2016; Scherbaum, Gottschalk, Dshemuchadse, & Fischer, 2015; Renas, Durst, & Janczyk, 2018; see also Schuch, Dignath, Steinhauser, & Janczyk, 2018). This is also the case for older adults (Janczyk, Mittelstädt, & Wienrich, 2018) and for 5–6-year-old children (Janczyk, Büschelberger, & Herbort, 2017), although for children the reasons might be different compared to (older) adults. The reduced compatibility-based BCE following incompatible trials has mostly been explained by more efficient shielding of Task 1 against influences of Task 2 (Fischer, Gottschalk, & Dreisbach, 2014; Janczyk, 2016). Alternatively, Task 2 RA might become more suppressed in this case and thus there is nothing that can influence Task 1 processing any longer.

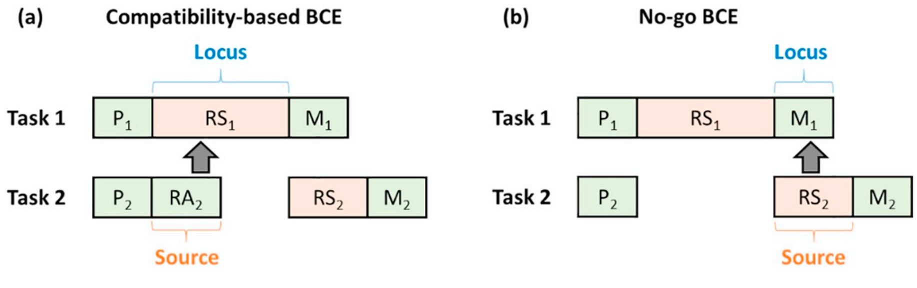

Fig. 1. Illustration of the locus (blue brackets) and the source (orange brackets) of the two BCEs under investigation here (see, e.g., Janczyk, Renas, et al., 2018, Durst & Janczyk, 2018; and others). (a) Compatibility-based BCE and (b) no-go BCE. (P = perceptual stage, RS = response selection, RA = response activation, M = motor stage, the subscript indicates Task 1 and 2, respectively). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

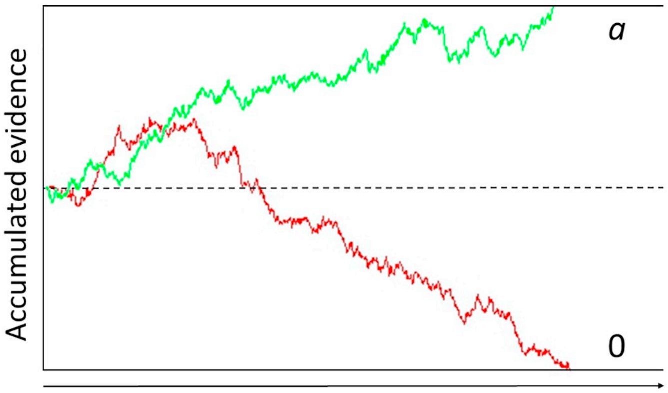

Fig. 2. Exemplary illustration of decision processes in the diffusion model. The two thresholds (here associated with correct [a] and erroneous responses [0]) are separated by the threshold separation a. The accumulation process moves with drift rate ν from the starting point (here centered between thresholds) until it reaches the upper or lower threshold. To the decision process depicted in the figure add non-decisional processes (e.g., encoding of information, motoric response execution). The green line illustrates a decision process leading to a correct response and the red line illustrates a decision process leading to a wrong response. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

For the no-go BCE, no sequential modulation has been reported so far and it remains an open question whether the no-go BCE is also subject to trial-by-trial adjustments in a similar way. As will be outlined below in the section on predictions, there are reasons to assume this, however.

While most previous studies on backward crosstalk and its sequential modulations focused on RTs and error data as the main dependent measures, we here go a step beyond and apply the diffusion model (Ratcliff, 1978) to our data. This allows (1) to further test the models depicted in Fig. 1 and (2) also to uncover the reasons for the sequential modulations, which will both help to specify the distinction between both BCEs. A brief introduction to the diffusion model is provided in the next section before we outline the present study and the predictions in more detail.

1.3. *A brief introduction into the diffusion model*

The diffusion model (Ratcliff, 1978) is a mathematical model of human decision making in binary tasks (see Fig. 2). It assumes that an individual accumulates evidence for a decision until one of two thresholds is reached. As soon as the threshold is hit, the decision is made and the according response is given. The standard diffusion model contains three main parameters: The drift rate v reflects the (average) speed and direction of information accumulation. In accordance with this, v is higher for easier tasks than for difficult ones (e.g., Germar, Schlemmer, Krug, Voss, & Mojzisch, 2014; Voss, Rothermund, & Brandtstädter, 2008; Voss, Rothermund, & Voss, 2004). Another important parameter is non-decision time (t_0), which reflects the duration of processes occurring before and after the decision process proper. Such processes are, for instance, perceptual or motor processes. Of particular importance for the present purposes, several manipulations affecting motor processes (e.g., blockwise altering response modalities, Gomez, Ratcliff, & Childers, 2015; movement distance to the response key, Voss et al., 2004; motor complexity, Lerche & Voss, 2017) were indeed reflected in t_0. Finally, the threshold separation a defines the amount of information that is needed to reach a decision, and can thus reflect speed-accuracy settings (for other manipulations affecting a, see Naefgen, Dambacher, & Janczyk, 2018). Evidence accumulation usually starts in the middle of both thresholds, although a bias towards one threshold can be implemented as well. In addition, while the drift rate drives the evidence into one direction in each time-step, random noise is added as well. This noise makes the diffusion process hit the correct threshold at various points in time and can also lead to its ending at the opposite threshold. In the latter case, an error is committed.

There are many publications on the diffusion model and its experimental validation, and we refer the reader to those instead of repeating the information here (for introductory articles, see Ratcliff, Smith, Brown, & McKoon, 2016; Voss, Nagler, & Lerche, 2013; for empirical studies with the diffusion model see, e.g., Schmitz & Voss, 2012; Janczyk & Lerche, 2018; Ratcliff, Thapar, & McKoon, 2011; Schubert, Hagemann, Voss, Schankin, & Bergmann, 2015). In relation to the compatibility-based BCE, only two previous studies have applied the diffusion model so far, but both focused only on Trial n. The prevalent impression from these studies is that drift rate was higher in compatible compared with incompatible trials (which is in line with a locus in RS; Janczyk, Renas, et al., 2018), at least for young and older adults (Janczyk, Mittelstädt, et al., 2018). For children, the effect was represented more in non-decision time (Janczyk et al., 2017).

1.4. *The present study and predictions*

The aims of the present study were twofold. First, we aimed at determining whether a sequential modulation can also be observed for the no-go BCE. Second, given this, we wanted to investigate the reasons for these sequential modulations in more detail, and our theoretical considerations (Durst & Janczyk, 2018; Janczyk, Renas, et al., 2018) suggest different loci that would be reflected in different parameters of the diffusion model. This assumption, so far based on behavioral measures and chronometric approaches carried out independently for both BCEs, would receive further and novel support if we could identify different reasons for the sequential modulations in both BCEs as reflected in different parameters of the diffusion model. Furthermore, this would help to specify the mechanisms which adjust cognitive control in both types of BCEs. To allow for a first direct comparison of both types of BCEs, the same participants provided data for both types of BCEs in two separate sessions. In the following, we will formulate specific predictions focusing on Task 1. Subsidiary hypotheses and the respective results concerning Task 2 can be found in the Appendix.

We will present the main hypotheses separately for both types of BCEs and for behavioral measures (RTs, error rates) and diffusion model parameters. Let us first consider the **compatibility-based BCE**:

- *Behavioral measures*. As reported in previous studies, we expected to observe a sequential modulation with a larger BCE following compatible relative to following incompatible trials (e.g., Janczyk, 2016).
- *Diffusion model parameters*. Considering that the compatibility-based BCE has its locus in Task 1 RS (Janczyk, Renas, et al., 2018; Thomson et al., 2015) and that drift rate v has been reported to be larger in compatible than in incompatible trials (Janczyk, Mittelstädt, et al., 2018), we expected the sequential modulation to be reflected in a sequential modulation of Task 1 drift rate v.
  While this is the primary prediction, we also predict an interaction of compatibility in Trial $n-1$ and Trial n for t_0. This prediction is due to the particular experimental setup in which the two transitions 'incompatible → incompatible' and 'compatible → compatible' entail 50% trials with exact repetitions of the two responses (see also Fig. 1 in Janczyk, 2016). Previous research has shown that such repetitions lead to shorter RTs due to re-usage of motor programs (e.g., Rosenbaum, Weber, Hazelett, & Hindorff, 1986).[1]

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[1] To foreshadow, this is what we observed. Thus, we also re-analyzed data from Experiment 3 in Janczyk (2016), where such transitions were avoided, and we expected to replicate the sequential modulation in drift rate v, but this time not in non-decision time t_0.

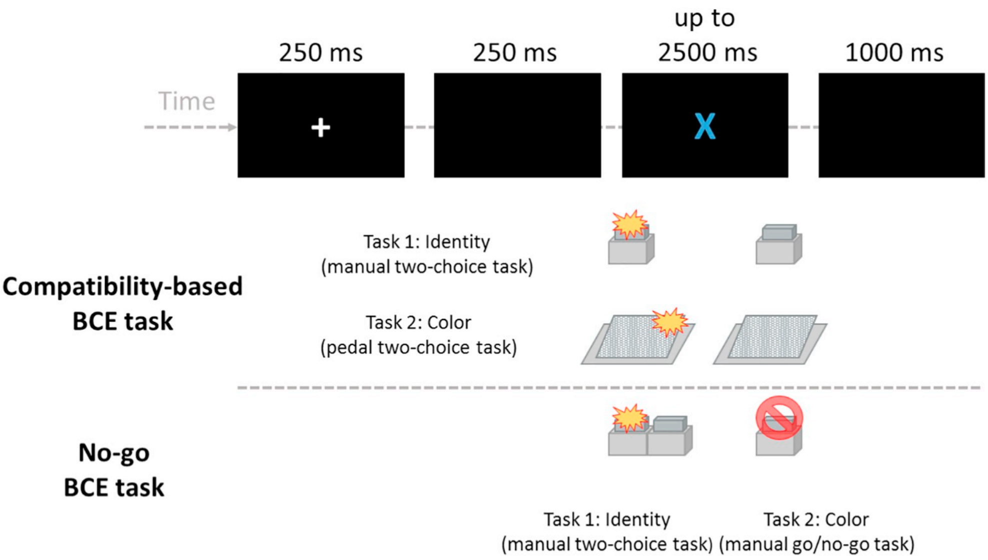

Fig. 3. Graphical illustration of the trial structure and the tasks performed for the compatibility-based BCE and the no-go BCE. In the compatibility-based BCE task, participants first responded to the identity of the letter in a manual two-choice task and subsequently to the color of the letter in a pedal two-choice task. In this particular example, an X calls for a manual response with the left key, while the color blue calls for a left pedal response, and thus both responses in Trial *n* are spatially compatible. In the no-go BCE task, participants first respond to the identity of the letter in a manual two-choice task with their left hand and subsequently to the color of the letter with a go/no-go task using their right index finger. In this particular example, an X calls for a response with the left middle finger, while the color blue indicates a no-go trial. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Regarding the **no-go BCE**, a sequential modulation has not been reported to date. Yet, it can be expected, but for different reasons than for the compatibility-based BCE. Consider that the no-go BCE is caused by inhibition required to overcome a prepared Task 2 response in a no-go trial (Janczyk & Huestegge, 2017; Miller, 2006) which spills over to Task 1 motor execution (Durst & Janczyk, 2018). We further assume that participants would adjust their response preparation of Task 2 in Trial *n* according to the preparation state induced by Trial $n-1$, similar to what was observed in stop-signal studies where an already prepared response has to be inhibited (Bissett & Logan, 2011). In other words, following go trials, participants (again) prepare the Task 2 response, which should lead to a no-go BCE in the case of a no-go trial. In contrast, following no-go trials, participants may not prepare the Task 2 response, and, thus no no-go BCE should be observed because the Task 2 response would not have to be inhibited. More precisely:

- *Behavioral measures*. Following go trials, we predict shorter RT1s in go compared to no-go trials.
- *Diffusion model parameters*. According to our assumption and the model presented in Fig. 1b, the sequential modulation is predicted to be reflected in non-decision time t_0, accordingly. Alternatively, a response selection locus of the no-go BCE was suggested by Ko and Miller (2014) and also, the no-go BCE might involve an abstract incompatibility of go versus no-go representations (Röttger & Haider, 2017). These accounts suggest a reflection in drift rate v as more likely.

In a nutshell, we expected to observe sequential modulations of the compatibility-based and the no-go BCE in the behavioral data and in the diffusion model parameters. The compatibility-based BCE was expected to be reflected mainly in drift rate v, whereas the no-go BCE was expected to be reflected in non-decision time t_0.

2. Method

2.1. Participants

Forty-eight students (37 female) from the University of Tübingen, aged 20 to 37 years ($M = 24.4$ years, $SD = 4.0$), participated for monetary compensation (16€) or course credit. All participants provided written informed consent prior to data collection and had normal or corrected-to-normal vision.

The effect of interest in our experiments is a 2 × 2 interaction of two repeated-measures which can be broken down to a (paired) *t*-test. A corresponding analysis of Janczyk's (2016) Experiment 3 data revealed $d_z = 0.66$ (without correction by multiplication with $\sqrt{2}$), that is, a medium-to-large effect according to Cohen (1988). To calculate our sample size, we thus assumed a medium effect of $d_z = 0.5$, $\alpha = 0.05$, and $1-\beta = 0.90$. Power analysis using the function power.t.test() of the R-software yielded a required sample size of $n \approx 44$ participants.

2.2. Apparatus and stimuli

A standard PC was used for stimulus presentation and response collection. Stimuli and instructions were presented on a 17-in. CRT monitor. Stimuli were the letters ‘H’ or ‘X’ colored in yellow or blue. The identity of the letter served as Stimulus 1 (S1) and the color of the letter served as Stimulus 2 (S2). Stimuli were presented in the center of an otherwise black screen. In the compatibility-based BCE session, responses to S1 were given via a manual key press of one of two response keys (R1), one to the left and one to the right of the participant on the table. Responses to S2 were given via a pedal press of one of two pedals (R2), one to the left and one to the right of the participant on the floor. In the no-go BCE session, responses to S1 were given via a manual key press of one of two response keys (R1), both placed to the left of the participant. Responses to S2 were given via a key press of a single response key to the right of the participant, or by withholding the response (R2).

2.3. Task and procedure

The trial structure is illustrated in Fig. 3. In the compatibility-based task, Task 1 was to respond to S1 with a key press of the left or right index finger, and Task 2 was to respond to S2 with a left or right pedal press. In the no-go task, Task 1 was to respond to S1 via a key press of the left index or middle finger, and Task 2 was to respond to S2 with a key press of the right index finger (go trial) or by withholding the response (no-go trial).

Every trial started with a white fixation cross (250 ms), followed by a blank screen (250 ms). Subsequently, the colored letter was presented for a maximum of 2500 ms or until R1 and R2 were registered. The next trial started after an inter-trial interval (ITI) of 1000 ms. In case of wrong responses or general errors (no response within 2500 ms following stimulus onset, responses in the wrong order, response to S2 in a no-go trial, and so on), specific error feedback was provided for 1000 ms before the ITI. (Such trials were excluded for analyses.)

Participants first performed a short familiarization block of 20 randomly drawn trials, which was followed by eighteen experimental blocks of 48 trials each, resulting from twelve repetitions of all combinations of 2 S1 × 2 S2. All trials were presented in a random order. Participants received written instructions that emphasized speed and accuracy, and were asked to give R1 and R2 successively in fixed order. The stimulus-response mapping of all tasks was counterbalanced across participants. One half of participants started with the compatibility-based BCE session, and completed the no-go BCE session one day to a week later (and vice versa for the other half of participants). One single session lasted for approximately 45 min.

2.4. Design and analysis

For the compatibility-based BCE, trials in which both responses were emitted on the same side (i.e., left index finger and left foot, or right index finger and right foot) were considered compatible, whereas trials in which both responses were emitted on different sides (i.e., left index finger and right foot, or right index finger and left foot) were considered incompatible. For the no-go BCE, a trial was considered a go-trial when R2 was to be given. Otherwise, when R2 was to be withheld, the trial was considered a no-go trial. Data from the first two blocks were excluded from analyses. For the sequential analysis of RTs, only entirely correct trials were considered if Trial $n-1$ was also entirely correct. Additionally, the first trial of each block was excluded from data analyses, because for these trials no Trial $n-1$ was available. In addition, for the analysis of RTs, only trials with RT1s between 200 ms and 1500 ms were included, while for RT2 only trials with RT2s between 200 ms and 1900 ms were included, all other trials were considered outliers. Mean correct RTs and error rate (ER) were first submitted to a 2 × 2 × 2 Analysis of Variance (ANOVA) with the factors (1) Task (compatibility-based vs. no-go BCE), (2) type in Trial n and (3) type in Trial $n-1$ (for factors 2 and 3: compatible vs. incompatible [compatibility-based BCE], or go vs. no-go [no-go BCE]) as repeated-measures. The critical interaction indicating a sequential modulation is that between the latter two factors 2 and 3. Thus, if the three-way interaction was significant, we followed-up this initial analysis with two 2 × 2 ANOVAs separately for each task to further test whether the critical interaction is present or not in each task.

2.5. Modelling

The same outlier criteria as for RT analyses were applied. The diffusion model parameters were estimated for each individual and separately for each task, applying the Maximum Likelihood criterion implemented in fast-dm-30 (Voss & Voss, 2007; Voss, Voss, & Lerche, 2015). The upper threshold was associated with a correct response, while the lower one was associated with an error response. The starting point was fixed at the center of the two thresholds.[2] The parameter a was allowed to vary across Trial $n-1$, while v and t_0 were allowed to vary across Trial n and Trial $n-1$. Inter-trial variability of starting point and v were fixed to zero, while the inter-trial variability of t_0 (st_0) was estimated, because under these conditions the Maximum Likelihood criterion leads to very reliable parameter estimates (Lerche & Voss, 2016). Thus, in total, eleven parameters were estimated: $a_{n-1 \text{ compatible}}$, $a_{n-1 \text{ incompatible}}$, $v_{n \text{ compatible}, n-1 \text{ compatible}}$, $v_{n \text{ compatible}, n-1 \text{ incompatible}}$, $v_{n \text{ incompatible}, n-1 \text{ compatible}}$, $v_{n \text{ incompatible}, n-1 \text{ incompatible}}$, $t_{0\ n \text{ compatible}, n-1 \text{ compatible}}$, $t_{0\ n \text{ compatible}, n-1 \text{ incompatible}}$, $t_{0\ n \text{ incompatible}, n-1 \text{ compatible}}$, $t_{0\ n \text{ incompatible}, n-1 \text{ incompatible}}$, and st_0. The diffusion model parameters v and t_0 were first submitted to a 2 × 2 × 2 ANOVA with the factors (1) Task (compatibility-based vs. no-go BCE), (2) type in Trial n and (3) type in Trial $n-1$ (for factors 2 and 3: compatible vs. incompatible [compatibility-based BCE], or go vs. no-go [no-go BCE]), and the parameter a was first submitted to a 2 × 2 ANOVA with the factors (1) task (compatibility-based vs. no-go BCE) and (2) type in Trial $n-1$ (compatible vs. incompatible [compatibility-based BCE], or go vs. no-go [no-go BCE]) as repeated-measures. As for RTs and ERs, separate analyses per task were run if the three-way interaction (for v and t_0) or the two-way interaction (for a) turned out to be significant.

3. Results

3.1. Behavioral results

All mean RT1s are visualized in Fig. 4 (see also Table 1 for the compatibility-based BCE and Table 2 for the no-go BCE) and ERs in Task 1 are summarized in Table 1 (compatibility-based BCE) and in Table 2 (no-go BCE). The corresponding analyses for Task 2 can be found in the Appendix.

The most important results of the initial three-way ANOVA relate to the three-way interaction of Task and type in Trial n and in Trial $n-1$ for RT1s and ER1. This interaction was significant for both RT1s, $F(1,47) = 86.07$, $p < .001$, $\eta_p^2 = 0.65$, and ER1, $F(1,47) = 58.83$, $p < .001$, $\eta_p^2 = 0.56$ (details of the full results are provided in Table 3). Accordingly, the sequential modulations differed significantly for the compatibility-based BCE and the no-go BCE, and we continue with the follow-up ANOVAs omitting the factor Task.

For the **compatibility-based BCE task**, the ANOVA for mean RT1s (0.76% outliers) revealed 30 ms longer RT1s for incompatible (548 ms) compared to compatible trials (518 ms), and thus a compatibility-based BCE, $F(1,47) = 38.52$, $p < .001$, $\eta_p^2 = 0.45$. RT1s were 8 ms longer following compatible (537 ms) relative to incompatible (529 ms) Trials $n-1$, $F(1,47) = 6.68$, $p = .013$, $\eta_p^2 = 0.12$. Most importantly, the interaction of type in Trial n and in Trial $n-1$ was significant, $F(1,47) = 231.90$, $p < .001$, $\eta_p^2 = 0.83$, and thus a sequential modulation of the compatibility-based BCE occurred. The compatibility-based BCE was present following compatible trials (121 ms), $t(47) = 6.08$, $p < .001$, $d = 0.88$ (here and in the following, d was calculated as $d = \frac{t}{\sqrt{n}}$), and inverted following incompatible trials (−63 ms), $t(47) = -7.88$, $p < .001$, $d = -1.14$.

The ANOVA for ER1 revealed a significant main effect of type in Trial n, with 1.84% more errors in incompatible (4.41%) relative to compatible trials (2.57%), $F(1,47) = 26.50$, $p < .001$, $\eta_p^2 = 0.36$. ER1 were on average 1.34% higher following compatible (4.16%) relative to incompatible trials (2.82%), $F(1,47) = 26.07$, $p < .001$, $\eta_p^2 = 0.36$. The interaction was also significant, $F(1,47) = 63.18$, $p < .001$, $\eta_p^2 = 0.57$, indicating a sequential modulation of the compatibility-based BCE. The compatibility-based BCE was present following compatible trials (6.60%), $t(47) = 5.34$, $p < .001$, $d = 0.77$, and inverted following incompatible trials (−2.91%), $t(47) = -4.36$, $p < .001$, $d = -0.63$.

For the **no-go BCE task**, the ANOVA for mean RT1s (0.60% outliers) revealed a significant main effect of type in Trial n, with 26 ms shorter RT1s for go (484 ms) relative to no-go trials (510 ms), and thus a no-go BCE, $F(1,47) = 56.12$, $p < .001$, $\eta_p^2 = 0.54$. RT1s were 22 ms shorter following go trials (487 ms) than following no-go trials (509 ms), $F(1,47) = 27.29$, $p < .001$, $\eta_p^2 = 0.37$. Most importantly, the interaction of type in Trial n and Trial $n-1$ was also significant, $F(1,47) = 123.50$, $p < .001$, $\eta_p^2 = 0.72$, indicating a sequential modulation. The no-go BCE was present following go trials (70 ms), $t(47) = 13.25$, $p < .001$, $d = 1.91$, and inverted following no-go trials (−18 ms), $t(47) = -3.30$, $p = .002$, $d = -0.48$. The ANOVA for ER1 revealed no significant effects, all Fs ≤ 1.47, all ps ≥ .231.

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[2] Note, that we decided to keep the starting point fixed, because in the literature there is no indication about how the starting point would vary depending on Trial $n-1$ and on Trial n, and because we had no hypothesis in this regard.

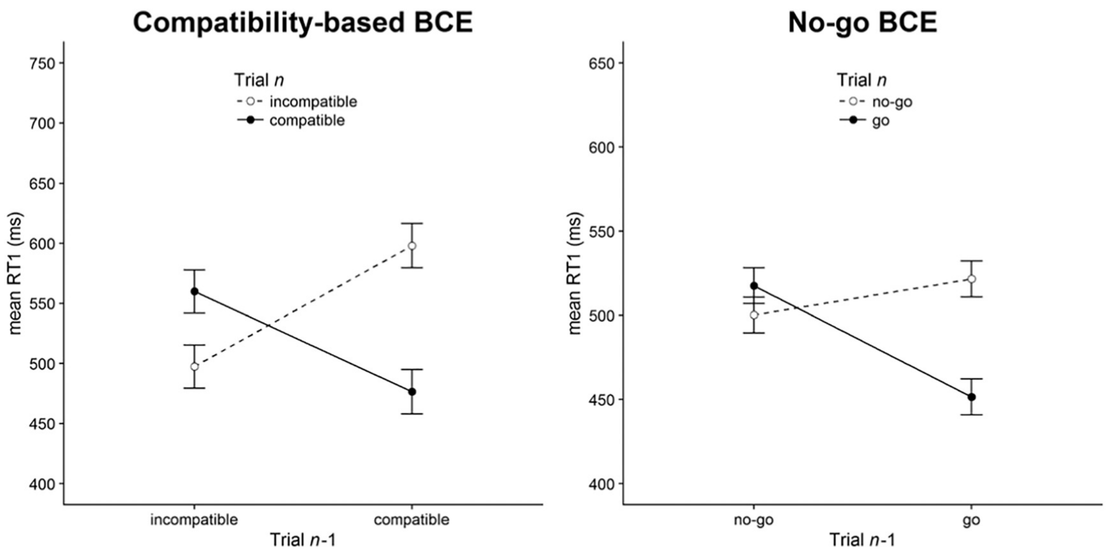

Fig. 4. Mean RTs of Task 1 as a function of type in Trial *n* (incompatible vs. compatible, or no-go vs. go) and Trial $n - 1$ (incompatible vs. compatible, or no-go vs. go) and task (compatibility-based BCE, left panel vs. no-go BCE, right panel). Error bars are 95% within-subject confidence intervals for the difference between type in Trial *n* (see Pfister & Janczyk, 2013).

Table 1

Mean RTs (in ms) and Error Rates (ER, in %) for Task 1 of the compatibility-based BCE task as a function of type in Trial *n* and Trial $n - 1$ (in ms). Crosstalk effects were computed by subtracting values from compatible trials from those of incompatible trials of Trial *n* line-by-line. (Note: DV = dependent variable).

DV	Trial $n - 1$	Trial *n*		
		Incompatible	Compatible	BCE
RT	Incompatible	497	560	−63
	Compatible	598	477	121
ER	Incompatible	1.37	4.28	−2.91
	Compatible	7.46	0.86	6.60

Table 2

Mean RTs (in ms) and Error Rates (ER, in %) for Task 1 of the no-go BCE task as a function of type in Trial *n* and Trial $n - 1$ (in ms). Crosstalk effects were computed by subtracting values from go trials from those of no-go trials of Trial *n* line-by-line. (Note: DV = dependent variable).

DV	Trial $n - 1$	Trial *n*		
		No-go	Go	BCE
RT	No-go	500	518	−18
	Go	522	452	70
ER	No-go	3.06	2.68	0.38
	Go	3.08	3.03	0.05

3.2. Summary of behavioral results

Significant interactions between type in Trial *n* and Trial $n - 1$ were present in Task 1 data for both the compatibility-based and the no-go BCE in RTs and ERs. The compatibility-based BCE was larger following compatible relative to incompatible trials (where it was even inverted) and the no-go BCE was larger following go relative to no-go trials (where it was even inverted). Thus, the present results indicate that indeed both types of the BCE were sequentially modulated. The sequential modulation for the no-go BCE is reported for the first time here. We will now present the results from the diffusion model analyses.

Table 3

Inferential statistics for the three-way ANOVA on RT1 and ER1. (Note: DV = dependent variable).

DV	Effect	$F(1,47)$	p	η_p^2
RT1	Type in Trial *n*	84.71	< .001	0.64
	Type in Trial $n - 1$	6.02	= .018	0.11
	Task	13.79	= .001	0.23
	Type in Trial *n* × type in Trial $n - 1$	239.36	< .001	0.84
	Type in Trial *n* × task	0.30	= .585	0.01
	Type in Trial $n - 1$ × task	34.71	< .001	0.42
	Type in Trial *n* × type in Trial $n - 1$ × task	86.07	< .001	0.65
ER1	Type in Trial *n*	32.05	< .001	0.41
	Type in Trial $n - 1$	23.98	< .001	0.34
	Task	2.69	= .108	0.05
	Type in Trial *n* × type in Trial $n - 1$	52.58	< .001	0.53
	Type in Trial *n* × task	14.21	< .001	0.23
	Type in Trial $n - 1$ × task	13.90	= .001	0.23
	Type in Trial *N* × type in Trial $N - 1$ × task	58.83	< .001	0.56

3.3. Diffusion model results

In the initial three-way ANOVAs the interactions of Task, type in Trial *n* and in Trial $n - 1$ were significant for v, $F(1,47) = 24.11$, $p < .001$, $\eta_p^2 = 0.34$, and t_0, $F(1,47) = 28.04$, $p < .001$, $\eta_p^2 = 0.37$. This indicates that the sequential modulations of both parameters differed significantly for the compatibility-based BCE and the no-go BCE. Also, the two-way interaction for the parameter a, $F(1,47) = 6.64$, $p = .013$, $\eta_p^2 = 0.12$, was significant. The full results of these ANOVAs are provided in Table 4. We continued with the follow-up ANOVAs separately for each task.

An illustration of the model fit for Task 1 of the **compatibility-based BCE** can be found in Fig. 5. Descriptive parameter data are visualized in Fig. 6 (see also Table 5). The corresponding analyses for Task 2 can be found in the Appendix.

The ANOVA revealed that v was on average 0.34 larger when Trial *n* was compatible (3.30) relative to incompatible (2.96), $F(1,47) = 21.44$, $p < .001$, $\eta_p^2 = 0.31$, but it was not influenced by Trial $n - 1$, $F(1,47) = 0.60$, $p = .444$, $\eta_p^2 = 0.01$. Most importantly, the interaction of type in Trial *n* and Trial $n - 1$ was significant, $F(1,47) = 79.27$, $p < .001$, $\eta_p^2 = 0.63$. After incompatible Trials $n - 1$, v was on average 0.51 larger if the current Trial *n* was incompatible (3.41) relative to compatible (2.90), $t(47) = 3.39$, $p = .001$, $d = 0.49$, while

Table 4
Inferential statistics for the three-way ANOVA on the diffusion model parameters v, t_0, and a. (Note: DV = dependent variable).

DV	Effect	$F(1,47)$	p	η_p^2
v	Type in Trial n	6.03	= .018	0.11
	Type in Trial $n-1$	24.03	< .001	0.34
	Task	57.80	< .001	0.55
	Type in Trial n × type in Trial $n-1$	0.98	= .327	0.02
	Type in Trial n × task	2.71	= .106	0.05
	Type in Trial $n-1$ × task	48.85	< .001	0.51
	Type in Trial n × type in Trial $n-1$ × task	24.11	< .001	0.34
t_0	Type in Trial n	0.10	= .754	< 0.01
	Type in Trial $n-1$	21.15	< .001	= 0.31
	Task	187.38	< .001	= 0.80
	Type in Trial n × type in Trial $n-1$	1.84	= .182	= 0.04
	Type in Trial n × task	25.61	< .001	= 0.35
	Type in Trial $n-1$ × task	2.63	= .112	= 0.05
	Type in Trial n × type in Trial $n-1$ × task	28.04	< .001	0.37
a	Type in Trial $n-1$	57.70	< .001	0.55
	Task	2.75	= .104	0.06
	Type in Trial $n-1$ × task	6.64	= .013	0.12

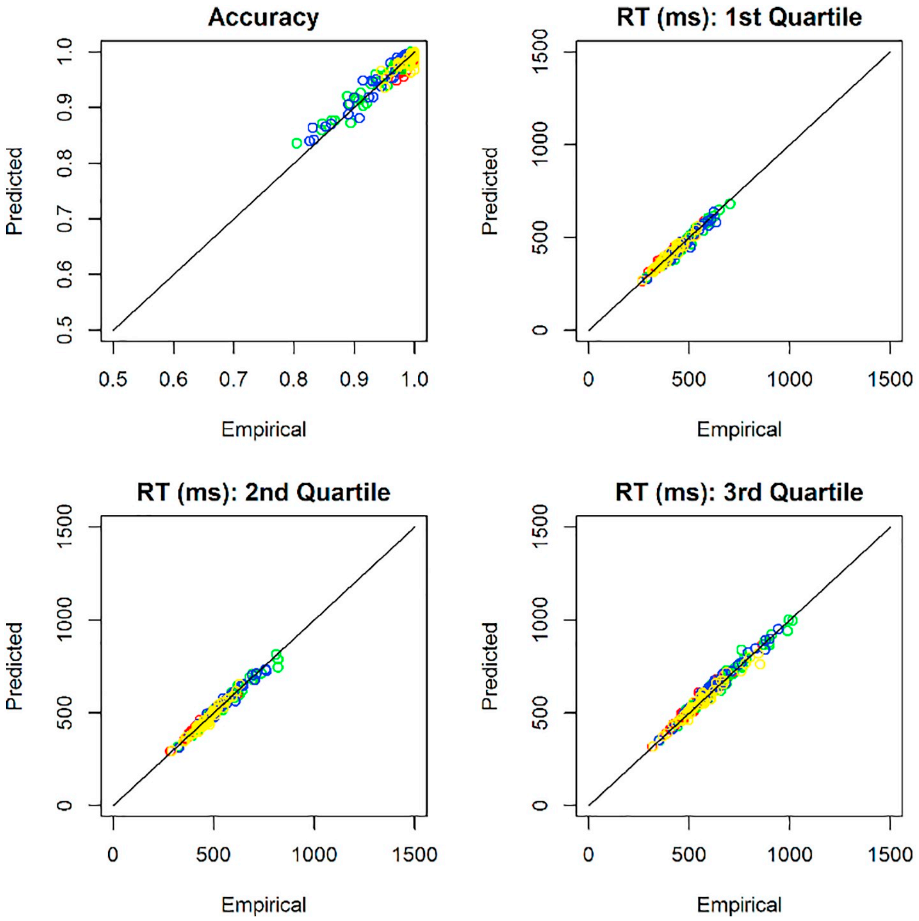

Fig. 5. Illustration of the model fit for the compatibility-based BCE Task 1: relationship between empirical and predicted statistics (accuracy, 1st, 2nd, and 3rd RT quartile). Red circles represent type in Trial n and Trial $n-1$ compatible, green circles represent type in Trial n incompatible and type in Trial $n-1$ compatible, blue circles represent type in Trial n compatible and type in Trial $n-1$ incompatible, and yellow circles represent type in Trial n and Trial $n-1$ incompatible means. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

after compatible Trials $n-1$, v was on average 1.19 larger if Trial n was compatible (3.71) relative to incompatible (2.51), $t(47) = -4.15$, $p < .001$, $d = -0.60$.

t_0 was neither affected by Trial n, $F(1,47) = 0.56$, $p = .460$, $\eta_p^2 = 0.01$, nor by Trial $n-1$, $F(1,47) = 0.32$, $p = .572$, $\eta_p^2 = 0.01$. However, the ANOVA also revealed a significant interaction of type in Trial n and Trial $n-1$, $F(1,47) = 144.81$, $p < .001$, $\eta_p^2 = 0.75$. After incompatible Trials $n-1$, t_0 was on average 0.04 larger for compatible (0.32) relative to incompatible (0.28) Trials n, $t(47) = -11.02$, $p < .001$, $d = -1.59$, while after compatible Trials $n-1$, t_0 was on average 0.05 larger for incompatible (0.32) relative to compatible (0.27) Trials n, $t(47) = -0.09$, $p = .928$, $d = -0.01$. In other words, the trial transitions that entailed 50% repetitions of responses had shorter non-decision times than the other transitions had.

Finally, the ANOVA revealed, that a was not influenced by type in Trial $n-1$, $F(1,47) = 0.66$, $p = .422$, $\eta_p^2 = 0.01$.[3]

An illustration of the model fit for Task 1 of the **no-go BCE** can be found in Fig. 7. Descriptive parameter data are visualized in Fig. 8 (see also Table 6). The corresponding analyses for Task 2 can be found in the Appendix.

For v, the main effect of type in Trial n was significant, with an on average 0.18 larger v in go (3.72) relative to no-go (3.54) trials, $F(1,47) = 6.66$, $p = .013$, $\eta_p^2 = 0.12$. Type in Trial $n-1$ also affected v, with an on average 0.14 larger v following go (3.70) than no-go (3.56) trials, $F(1,47) = 5.24$, $p = .027$, $\eta_p^2 = 0.10$. The interaction was not significant, $F(1,47) = 2.33$, $p = .134$, $\eta_p^2 = 0.05$. The ANOVA for t_0 revealed an on average 0.02 larger t_0 for no-go (0.34) relative to go (0.32) trials, $F(1,47) = 43.45$, $p < .001$, $\eta_p^2 = 0.48$. Type in Trial $n-1$ did not affect t_0, $F(1,47) = 1.50$, $p = .227$, $\eta_p^2 = 0.03$. Most importantly, the interaction of type in Trial n and Trial $n-1$ was significant, $F(1,47) = 111.20$, $p < .001$, $\eta_p^2 = 0.70$. After no-go trials, t_0 was on average 0.02 larger for go (0.34) relative to no-go trials (0.32), $t(47) = -3.85$, $p < .001$, $d = -0.56$, while after go trials, t_0 was on

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[3] Correlations between the three parameters were calculated for each of the four design cells. Because a was only estimated as a function of Trial $n-1$ compatibility, the respective values were used in the relevant two design cells. In the following, we report the range of the four calculated correlations for each parameter combination: $r(v,a) = [-0.45;\ 0.23]$, $r(v,t_0) = [-0.24;\ -0.01]$, $r(a,t_0) = [-0.13;\ 0.15]$.

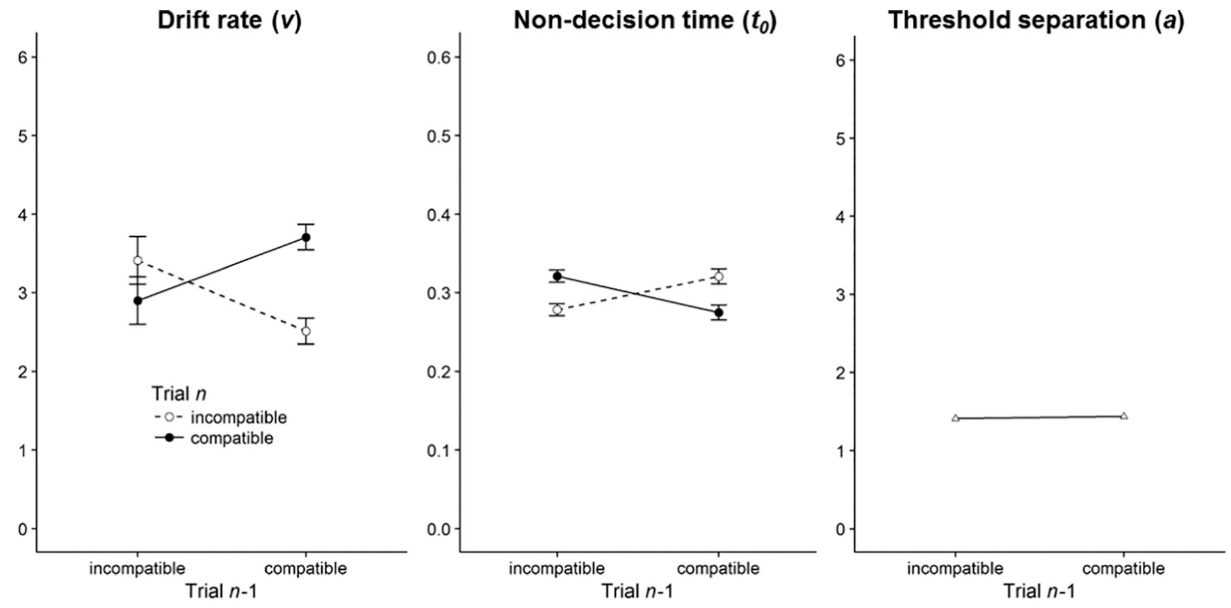

Fig. 6. Mean diffusion model parameters for Task 1 of the compatibility-based BCE task: v and t_0 as a function of type in Trial n and Trial $n-1$ (for both factors: incompatible vs. compatible), and a as a function of type in Trial $n-1$ (incompatible vs. compatible). Errors bars are 95% within-subject confidence intervals for the difference between type in Trial n incompatible and compatible (see Pfister & Janczyk, 2013).

Table 5
Mean parameter values of, drift rate (v), non-decision time (t_0), and threshold separation (a) for Task 1 of the compatibility-based BCE task as a function of type in Trial n (only v and t_0) and Trial $n-1$. (Note: DV = dependent variable).

DV	Trial $n-1$	Trial n	
		Incompatible	Compatible
v	Incompatible	3.41	2.90
	Compatible	2.51	3.71
t_0	Incompatible	0.28	0.32
	Compatible	0.32	0.27
a	Incompatible	1.41	
	Compatible	1.44	

average 0.06 larger for no-go (0.36) relative to go (0.30) trials, $t(47) = 13.65$, $p < .001$, $d = 1.97$.

Finally, the ANOVA revealed an on average 0.08 larger a following no-go (1.19) than go trials (1.11), $F(1,47) = 15.38$, $p < .001$, $\eta_p^2 = 0.25$.[4]

3.4. *Reanalysis of Experiment 3 in Janczyk (2016)*

This particular experiment employed a standard compatibility-based BCE task, but full repetitions and full alternations of stimuli were not allowed and repetitions of response combinations did not occur in all four possible compatibility transitions. Nonetheless, a sequential modulation of the BCE was observed, which was only present following compatible trials, but entirely absent following incompatible trials. For the reanalysis, the same diffusion model and outlier criteria as in the present study were applied.

An illustration of the model fit for Task 1 can be found in Fig. 9. Descriptive parameter data are visualized in Fig. 10 (see also Table 7). The corresponding analyses for Task 2 can be found in the Appendix.

Neither type in Trial n, $F(1,31) = 0.14$, $p = .708$, $\eta_p^2 < 0.01$, nor type in Trial $n-1$, $F(1,31) = 0.28$, $p = .599$, $\eta_p^2 = 0.01$, affected v. Importantly, the sequential modulation was significant for v, $F(1,31) = 4.51$, $p = .042$, $\eta_p^2 = 0.13$. Following incompatible trials, v was on average 0.68 larger for incompatible (2.94) relative to compatible trials (2.26), $t(31) = 2.49$, $p = .019$, $d = 0.44$, and following compatible trials, v was on average 0.59 larger in compatible (3.09) relative to incompatible trials (2.50), $t(31) = 0.72$, $p = .474$, $d = 0.13$.

For t_0, the analysis neither revealed a significant main effect of type in Trial n, $F(1,31) = 0.15$, $p = .702$, $\eta_p^2 < 0.01$, nor of type in Trial $n-1$, $F(1,31) = 0.68$, $p = .414$, $\eta_p^2 = 0.02$. Most importantly, the interaction was also not significant, $F(1,31) = 1.41$, $p = .243$, $\eta_p^2 = 0.04$. Thus, these results replicate the sequential modulation in drift rate v, but when repetitions of response combination did not occur, t_0 was *not* sequentially modulated.

Finally, a was not affected by type in Trial $n-1$, $F(1,31) = 0.52$, $p = .476$, $\eta_p^2 = 0.02$.[5]

4. General discussion

The main goals of the present study were to (1) investigate whether sequential modulations could be obtained for the compatibility-based BCE and in particular for the no-go BCE, and (2) to investigate the reason for the sequential modulation of both BCEs applying the diffusion model to the behavioral data of each BCE task. Our basic assumption underlying this research was that both types of BCEs are qualitatively different, that is, they occur for different reasons (see Fig. 1 for an illustration). By and large, the results strongly support this assumption.

In the following, we will summarize and discuss the main results separately for both types of BCEs. In a subsequent section, we will then conclude with comparing both BCEs regarding their underlying processes and the adjustment of cognitive control.

4.1. *The compatibility-based BCE*

As already earlier studies demonstrated (Janczyk, 2016; Renas et al., 2018; Scherbaum et al., 2015), a clear sequential modulation was observed in the behavioral data: The compatibility-based BCE was large

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[4] Correlations between parameters were calculated as described in Footnote 3: $r(v,a) = [-0.53; 0.45]$, $r(v,t_0) = [-0.15; 0.18]$, $r(a,t_0) = [0.07; 0.40]$.

[5] Correlations between parameters were calculated as described in Footnote 3: $r(v,a) = [-0.35; 0.96]$, $r(v,t_0) = [0.51; 0.75]$, $r(a,t_0) = [-0.49; 0.63]$.

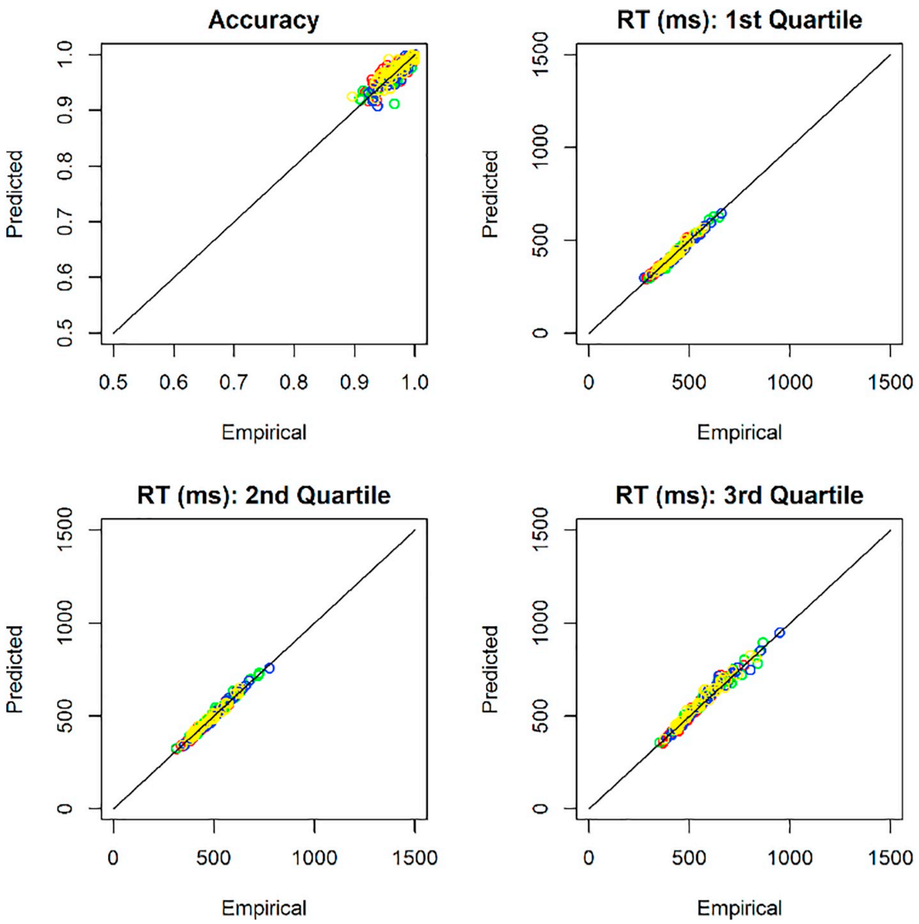

Fig. 7. Illustration of the model fit for the no-go BCE Task 1: relationship between empirical and predicted statistics (accuracy, 1st, 2nd, and 3rd RT quartile). Red circles represent type in Trial *n* and Trial $n - 1$ go, green circles represent type in Trial *n* no-go and type in Trial $n - 1$ go, blue circles represent type in Trial *n* go and type in Trial $n - 1$ no-go, and yellow circles represent type in Trial *n* and Trial $n - 1$ no-go means. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

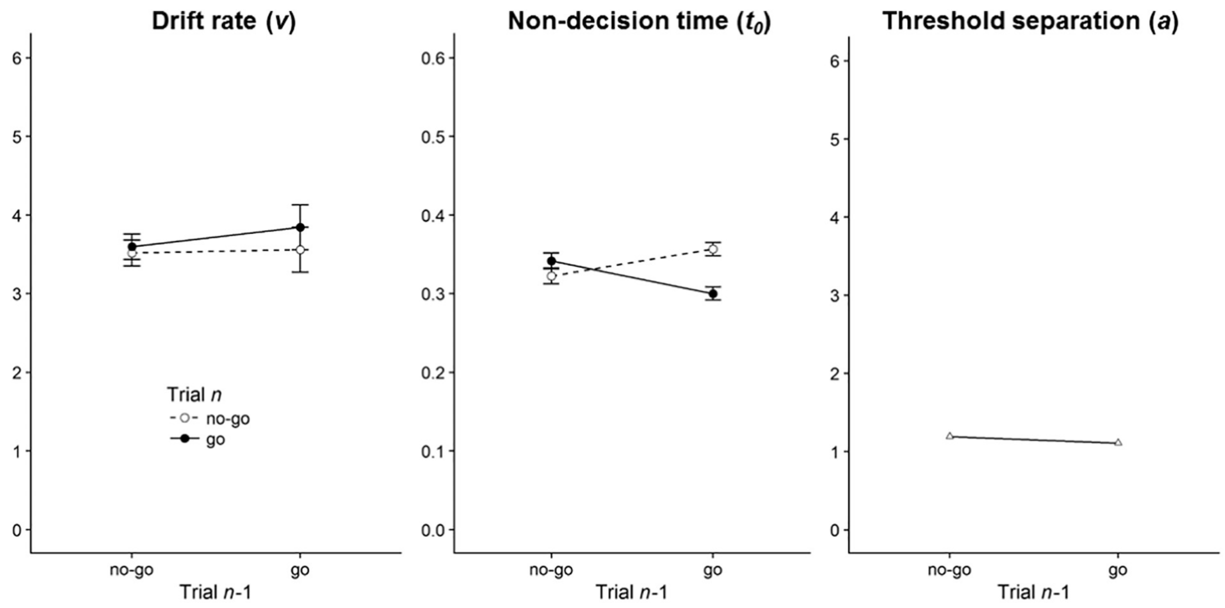

Fig. 8. Mean diffusion model parameters for Task 1 of the no-go BCE task: *v* and t_0 as a function of type in Trial *n* and Trial $n - 1$ (for both factors: no-go vs. go), and *a* as a function of type in Trial $n - 1$ (no-go vs. go). Errors bars are 95% within-subject confidence intervals for the difference between type in Trial *n* no-go and go (see Pfister & Janczyk, 2013).

following compatible trials, and absent, or more precisely: even inverted, following incompatible trials. In addition, the sequential modulation was effectively reflected in the drift rate parameter *v* of the diffusion model. This was expected against the background of previous studies that identified the RS stage of Task 1 as the locus of this type of BCE (Janczyk, Renas, et al., 2018; Thomson et al., 2015; for evidence from the LRP see Lien et al., 2007; Miller, 2017). In particular, following compatible trials, it appeared as if RA resulting from Task 2 was added to that of Task 1, eventually resulting in an increased drift rate in compatible trials and a decreased drift rate in incompatible trials. A

Table 6
Mean parameter values of drift rate (v), non-decision time (t_0), and threshold separation (a), for Task 1 of the no-go BCE task as a function of type in Trial n (only v and t_0) and Trial $n - 1$. (Note: DV = dependent variable).

DV	Trial $n - 1$	Trial n	
		No-go	Go
v	No-go	3.52	3.60
	Go	3.56	3.84
t_0	No-go	0.32	0.34
	Go	0.36	0.30
a	No-go	1.19	
	Go	1.11	

similar idea was already envisaged in the ECTVA model (Logan & Gordon, 2001), where response information from Task 2 is (erroneously) added to Task 1 response counters. Alternatively, it may be possible that Task 1 RS, as reflected by Task 1 drift rate, is superimposed by a second diffusion process reflecting parallel-running Task 2 RA, as was envisaged in the Diffusion Model for Conflict tasks (DMC; see Ulrich et al., 2015). Possible extensions of the DMC to the dual-task situation are illustrated in Fig. 11, for two different scenarios of the Task 2 RA time-course. In the left panel (Model A), the time-course resembles that assumed for conflict tasks in the DMC: The Task 2 RA activation quickly rises and declines again to zero. Alternatively, against the background that the RA-inducing stimulus (feature) is not irrelevant to the whole task (as, e.g., are the flankers in a flanker experiment), Task 2 RA might steadily increase while Task 1 RS is still ongoing. This is visualized in the right panel (Model B). A modelling approach may also help to reveal whether information accumulated in Task 2 RA can be passed on to Task 2 RS or not. Some authors suggested that observing the same RT pattern for Task 2 as for Task 1 is completely due to propagation of Task 1 effects into Task 2 performance (Schubert et al., 2008), while others suggested that Task 2 RS in fact benefits from still available RA, at least in compatible trials (Thomson & Watter, 2013). Note that, in Fig. 11, we assumed that Task 2 RS starts at the still available level of existing RA. Interestingly, Model A in this figure allows for larger RT differences between compatible and incompatible trials in Task 2 than in Task 1, what has in fact been observed in several studies (e.g., Hommel, 1998; Logan & Gordon, 2001; Janczyk, 2016, Exp. 1/2; but see also Ellenbogen & Meiran, 2011). This work is currently ongoing in our lab.

Additionally, a sequential modulation of t_0 was obtained with the data from the present study, but not with the data from Experiment 3 in Janczyk (2016). The crucial difference between the two experiments is that in the present experimental setup two trial transitions comprise 50% of exact response repetitions; this did not occur in the data from the reanalyzed experiment. The sped-up responses with response repetitions (Rosenbaum et al., 1986) were apparently reflected in non-decision time t_0. Thus, while it seems clear that a part of processing responsible for the sequential modulation is attributable to RS-related processing, some part also is due to repetitions of responses, if those are present. Taken together, these results support the assumption that the sequential modulation of the compatibility-based BCE is based on a trial-to trial adjustment of v.

These results are, however, compatible with two different—yet not mutually exclusive—scenarios. First, the critical adjustment following incompatible trials may take place in Task 1, what has been termed “increased shielding of Task 1” in several papers (e.g., Fischer et al., 2014; Janczyk, 2016). Second, it might as well be the case that following incompatible trials, Task 2 RA is suppressed and can thus not affect Task 1 processing at all (similar to what has been suggested to

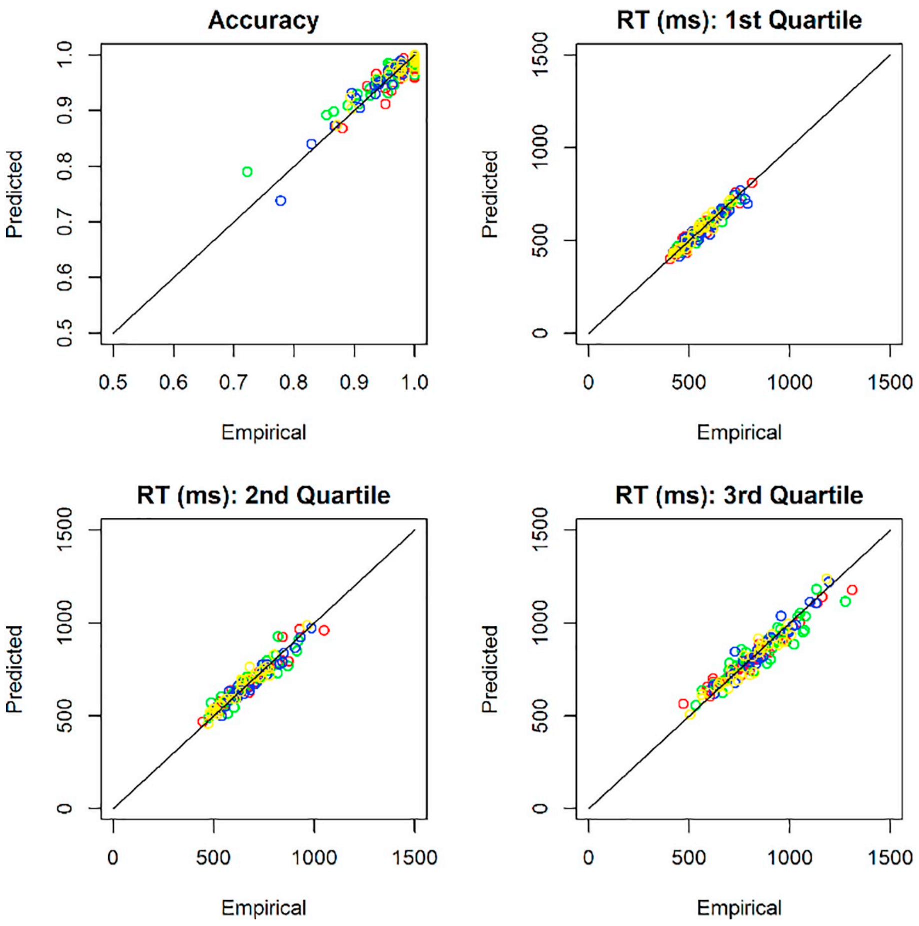

Fig. 9. Illustration of the model fit for the compatibility-based BCE Task 1 of the reanalysis of Janczyk (2016, Experiment 3): relationship between empirical and predicted statistics (accuracy, 1st, 2nd, and 3rd RT quartile). Red circles represent type in Trial n and Trial $n - 1$ go, green circles represent type in Trial n no-go and type in Trial $n - 1$ go, blue circles represent type in Trial n go and type in Trial $n - 1$ no-go, and yellow circles represent type in Trial n and Trial $n - 1$ no-go means. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

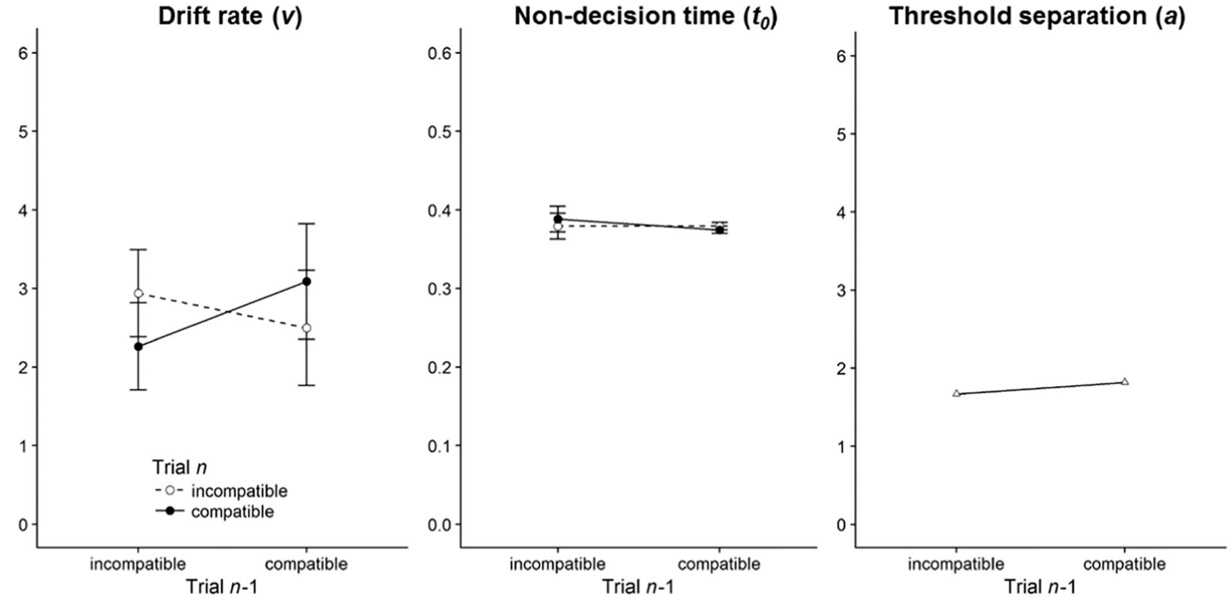

Fig. 10. Reanalysis of Janczyk (2016, Experiment 3). Mean diffusion model parameters for Task 1: v and t_0 as a function of type in Trial n and Trial $n - 1$ (for both factors: incompatible vs. compatible), and a as a function of type in Trial $n - 1$ (incompatible vs. compatible). Errors bars are 95% within-subject confidence intervals for the difference between type in Trial n incompatible and compatible (see Pfister & Janczyk, 2013).

Table 7
Mean parameter values of drift rate (v), non-decision time (t_0), and threshold separation (a) for Task 1 of the reanalysis of Janczyk (2016, Experiment 3) as a function of type in Trial n (only v and t_0) and Trial $n - 1$. (Note: DV = dependent variable).

DV	Trial $n - 1$	Trial n	
		Incompatible	Compatible
v	Incompatible	2.94	2.26
	Compatible	2.50	3.09
t_0	Incompatible	0.38	0.39
	Compatible	0.38	0.37
a	Incompatible	1.67	
	Compatible	1.82	

occur in standard conflict tasks; e.g., Janczyk & Leuthold, 2018; Stürmer et al., 2002; Stürmer & Leuthold, 2003). Inhibition of tasks has indeed been suggested as one mechanism supporting task switching (Mayr & Keele, 2000; see Koch, Gade, Schuch, & Philipp, 2010, for a review). Although the present study was not meant to address this issue directly, the Task 2 analyses presented in the Appendix can be taken to inform this question. Acknowledging a few significant effects of type in Trial $n - 1$ on Task 2 diffusion model parameters, the general impression is that such effects are absent, small, and/or unreliable. Thus, we suggest to tentatively take these results to conclude that Task 2 processing is essentially unaltered, but rather Task 1 processing is affected by experiencing incompatibility in Trial $n - 1$ by increased task shielding.

Admittedly, the term “increased task shielding” is little more than a description of observing a reduced BCE. How, then, can such task shielding be specified? Task sets have been suggested to function as a general mechanism to prevent interference from irrelevant information, by directing attention to the relevant features (Dreisbach & Haider, 2008, 2009). While our results do not speak in favor of Task 2 being suppressed (Koch et al., 2010; Mayr & Keele, 2000), the alternative would be that the task set of Task 1 is increased in activity, because

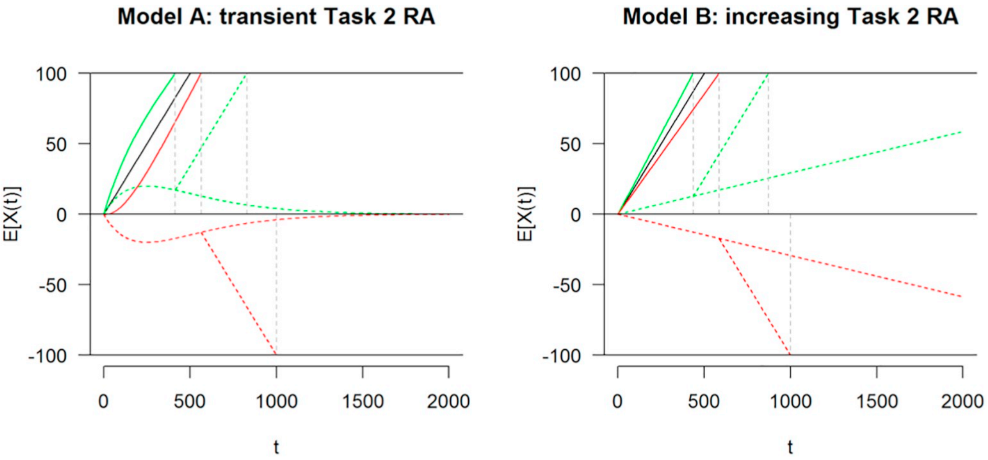

Fig. 11. Illustration of a conceivable DMC extension to dual-tasking for two models differing regarding the time-course of Task 2 RA. E[X(t)] denotes the expected activation as a function of time t. In both variants, an upper (a = 100) and a lower threshold (b = −a) are associated with one of two response directions (e.g., left vs. right). The solid black line represents the evidence that would result from the controlled Task 1 diffusion process only. However, because the automatic Task 2 RA is superimposed, the actual Task 1 activation is given by the solid green and red lines (for compatible and incompatible trials, respectively). The time-course of Task 2 RA is illustrated via the green and red dotted line, but importantly, it differs between both models. Model A assumes a time-course that corresponds to DMC which assumes a pulse function with a fast rise followed by declining activation, whereas Model B assumes a steadily increasing function. RS in Task 2 begins, when Task 1 RS exceeds a threshold and—in this depiction—begins at the level of the (still) existing Task 2 RA (but see Schubert et al., 2008; Thomson & Watter, 2013). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

participants may have the intention to shield it from interference (Goschke, 2003). This might go along with directing attention more to Task 1 demands (similar to how Botvinick et al., 2001, conceptualized cognitive control to operate in the Stroop task) or a facilitated perceptual processing in Task 1 (Stelzel, Brandt, & Schubert, 2009). By these means, interfering influences of ongoing Task 2 processing might be less effective, and consequently, the BCE becomes smaller. These accounts all assume that the purpose of any adaptation is to reduce the between task interference eventually resulting in a BCE.

A different perspective might perhaps be taken when considering that a strong task shielding mode is also experienced as more demanding (Lehle, Steinhauser, & Hübner, 2009). Perhaps, following a compatible trial, participants simply adopt a less demanding or more "natural" processing style, which has been shown to result in between-task crosstalk (Lehle & Hübner, 2009). Following this reasoning, the sequential modulation of the BCE would just be a by-product of the adjusted processing style. Future studies should investigate this issue more directly. One way would be to have participants experience a compatible or incompatible BCE trial and subsequently test to what extent Task 1 or Task 2 interfere more or less with an independent third task.

4.2. The no-go BCE

A novel observation of the present study is the sequential modulation of the no-go BCE. A standard no-go BCE with shorter RT1s in go compared with no-go trials was only present, if Trial $n - 1$ comprised a go trial as well. In contrast, if the previous trial comprised a no-go task, RT1s were even shorter in no-go compared with go trials. As predicted from our underlying model (see Fig. 1), this interaction was reflected in motor execution, that is, in the parameter t_0 (see also Durst & Janczyk, 2018, for behavioral evidence). In sum, we suggest that an active inhibition required in Task 2 no-go trials induces a generalized inhibition of the motor system (see already Miller, 2006), also prolonging RT1 as a consequence. In addition, although only a speculation at present, the induced inhibition might even be more general and account for the smaller drift rate v following no-go trials compared with following go trials. That no-go trials induce inhibition receives evidence also from other perspectives. For instance, it was shown that pairing appetitive stimuli with no-go responses led to devaluation of these stimuli, which was assumed to be caused by the repeated inhibition of a response to the according stimulus category (e.g., see Serfas, Florack, Büttner, & Voegeding, 2017). Additional behavioral and psychophysiological evidence for the existence of a generalized inhibition of the motor system was observed in the stop-signal paradigm (for a review see Wessel & Aron, 2017) and following the occurrence of unexpected events (Wessel & Aron, 2013).

What are the reasons for the sequential modulation, that is, why did the no-go BCE not occur in the usual way following no-go trials? We interpret this in a way that participants remain in a "prepare R2"-state following go trials, but that following no-go trials, preparation for R2 is decreased or absent. In the latter case, less or no inhibition is needed to suppress R2 and little or no inhibition spreads to Task 1 processing. The assumption that preparation for Task 2 is the crucial mechanism that adjusts cognitive control in the no-go BCE is further supported by the results for Task 2 (see Appendix), where RT2s were shorter following go than no-go trials and v was larger following go than no-go trials. These results are well in line with the idea that R2 preparation was increased following go trials.

As an alternative, already Botvinick et al. (2001) suggested that no-go tasks involve overriding a prepotent response which is registered in the same cortical area (the anterior cingulate cortex, ACC) as is the conflict arising from an incompatible flanker trial, for example (see, e.g., Donkers & van Boxtel, 2004; Nieuwenhuis, Yeung, van den Wildenberg, & Ridderinkhof, 2003). In an extension, Botvinick (2007) suggested that various conflict types have in common to induce negative affect, which is subsequently used as the signal to initiate adjustments (see also, e.g., Dreisbach & Fischer, 2015; Saunders, Lin, Milyavskaya, & Inzlicht, 2017). Such interpretation is in fact in line with the above mentioned observation that no-go tasks yield devaluation of stimuli (see Serfas et al., 2017).

Taken together, the present state of research allows two interpretations. First, performance adjustments in the no-go BCE task are based on the preparation state for Task 2 which requires to overcome a prepotent response via inhibition. Second, this requirement may be experienced as conflict and/or negative affect, which then triggers further adjustments (of which inhibition may be one). Future research is certainly needed, however, to address this point directly.

In a further sense, the present results may also be related and in line with the goal priority hypothesis known from the stop-signal paradigm (Leotti & Wager, 2010; Liddle et al., 2009), which assumes that participants prioritize the stop task over the go task following stop-signals and that the occurrence of stop-signals makes participants more cautious (Bissett & Logan, 2011). In the sense of the goal priority hypothesis, the inverted no-go BCE following no-go trials combined with the larger v following go relative to no-go trials indicates a prioritization of the no-go over the go Task 2, while the larger a following no-go relative to go trials indicates that participants became more cautious following no-go trials. While it may be tempting to interpret the present results in favor of the goal priority hypothesis it should be noted, that the no-go BCE task and the stop-signal paradigm differ in several aspects, and it is not yet completely resolved whether inhibition plays the exactly same role in both paradigms (Verbruggen & Logan, 2008).

4.3. Interim summary: two different types of BCEs

Taken together, the data from the present study—and in particular the results from the diffusion model analyses—confirm and extend the model depicted in Fig. 1. More precisely, the compatibility-based BCE seems to be located inside Task 1 RS and has its source in Task 2 RA (Janczyk, Renas, et al., 2018), while the no-go BCE is located inside Task 1 motor execution and has its source in T2 RS (Durst & Janczyk, 2018). In addition, both types of BCEs exhibit sequential modulations, but most likely for different reasons. In case of the compatibility-based BCE, experiencing an incompatible trial leads to conflict-induced adjustments resulting in increased Task 1 shielding, perhaps similar to what happens in standard conflict tasks. In contrast, a sequential modulation of the no-go BCE, we suggest, results if participants adopt their preparation of R2 depending on whether this response was required or not in the previous trial. These considerations are summarized in Fig. 12, and we believe they provide clear support for a theoretical distinction of both types of BCEs.

4.4. Caveats, limitations, and future directions

We consider the main results of the present study straightforward. In contrast to the main results, however, the results speaking to the subsidiary research questions (see Appendix), which mainly refer to Task 2 of the compatibility-based BCE, are not that clear cut. Even though the diffusion model parameter results seem not to support an account in terms of Task 2 suppression following incompatible trials, we wish to highlight the preliminary character of these results. Further, we suggest tentatively that Task 1 processing is altered, but the present data cannot indicate this account by themselves. Rather, an argument in favor of Task 1 shielding is solely based on a preliminary exclusion of Task 2 suppression. Future research is certainly required to explicitly address these accounts empirically.

It should also be noted that the two types of backward crosstalk under investigation here can also be produced with other combinations of effector systems (e.g., manual and vocal responses for the compatibility-based BCE: Renas et al., 2018; Hommel, 1998; and, e.g., manual and pedal responses for the no-go BCE: Janczyk & Huestegge, 2017,

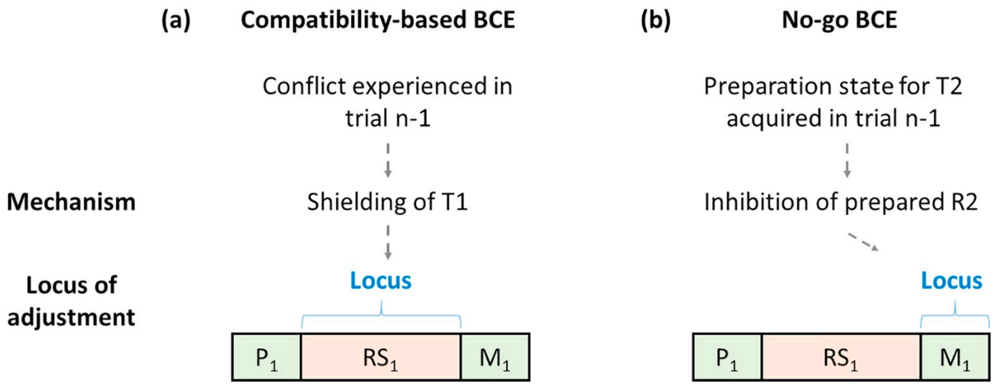

Fig. 12. Illustration of the mechanism, and locus of adjustment in Task 1 for (a) the compatibility-based BCE and (b) the no-go BCE. (P = perceptual stage, RS = response selection, M = motor stage).

Experiment 3b). We chose the effector system combinations of the present study for two reasons: (1) to ensure comparability with our previous studies and (2) because these effector system combinations—according to our experience—produce the largest effects. Yet, we do at present not see a reason why other effector system combinations should invoke entirely different processes and yield qualitatively different results.

The two types of BCEs under investigation here are not the only types that have been reported in the literature. For instance, studies that enabled a conceptual overlap between Task 1 and Task 2 (Logan & Delheimer, 2001; Logan & Schulkind, 2000; Oriet, Tombu, & Jolicoeur, 2005) reported that the stimulus category S2 belonged to influenced Task 1 performance in a way that RT1s were shorter when S2 was of the same vs. different category as S1. Other studies have reported BCEs based on aspects of Task 2 motor processes. For instance, Miller and Alderton (2006) reported that the amount of response force required in Task 2 influenced the force applied in Task 1, in a way that harder keypresses in Task 2 led to harder keypresses also in Task 1. In a similar vein, a study by Ruiz Fernández and Ulrich (2010) observed that the distance over which a lever was moved in Task 2 affected RT1s and response duration in Task 1. Further research should certainly compare the compatibility-based BCE and the no-go BCE to other types of overlap-based and motor execution based BCEs to help develop a more general framework of between-task crosstalk and to pinpoint which types of backward crosstalk can be distinguished based on their underlying processes and adjustment of cognitive control.

Furthermore, it should be noted that an issue inherent to any modelling approach is that other models may fit the present data equally well, and yet indicate different loci and sources for both BCEs than the ones we suggested here. We here applied the diffusion model, and thus its particular assumptions. For one we believe this is a warranted choice given the many applications of this model and the numerous validations available. At the same time, however, we acknowledge that other models exist that may account for the present data in other ways.

4.5. *Conclusion*

The present study aimed at providing converging evidence for a qualitative distinction of two types of backward crosstalk in dual-tasks. This idea (see Fig. 1 for an illustration) was largely built on previous behavioral studies (Durst & Janczyk, 2018; Janczyk, Renas, et al., 2018). Here we (1) tested for sequential modulations of both types of BCEs and (2) based our predictions not only on behavioral data but also on parameters derived from diffusion model analyses. By and large, the results support the qualitative distinction of compatibility-based BCEs and no-go BCEs and suggest that their sequential modulations also result for different reasons (see Fig. 12 for an integrative depiction).

Acknowledgements

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Appendix A. Predictions and results for Task 2

Our main hypotheses related to Task 1 and thus the respective predictions and results were reported in the main text. In this Appendix, we formulate several subsidiary hypotheses regarding the behavioral measures and the diffusion model parameters of Task 2. Admittedly, the (standard) diffusion model was not designed to estimate parameters for two tasks at the same time, and thus the predictions made in the following are more exploratory than those related to Task 1 performance. Nonetheless, we consider them and the respective results informative and required for completeness.

A.1. *Predictions*

Regarding the **compatibility-based BCE**, RT2s often show a similar sequential modulation as RT1s. Thus far, it is an unresolved question whether this is due only to propagation of Task 1 effects (Schubert et al., 2008) or to Task 2 RS benefitting from still available RA in Task 2, which has not vanished completely (Thomson & Watter, 2013, suggested this at least for compatible trials). While the present experiment was not meant to resolve this question, we believe that a diffusion model analysis of Task 2 data depending on type in Trial $n - 1$ may help illuminating the underlying mechanisms of the sequential modulation in RT1s further. We can conceive of two scenarios. (1) (In-)Compatibility in Trial $n - 1$ does not affect Task 2 RA in the following trial, but instead Task 1 processing is altered. A popular notion refers to increased "task shielding" in this case (Fischer et al., 2014; Janczyk, 2016). In a sense, this would be akin to the mechanisms suggested by Botvinick et al. (2001), for example, when for a Stroop task the relevant task set is activated more after experiencing conflict. In this case, we expect Task 2 diffusion model parameters being unaffected by type in Trial $n-1$. (2) It might as well be possible that after experiencing an incompatible trial, the subsequent Task 2 RA is suppressed. Put plainly, if no Task 2 RA exists, nothing can crosstalk to Task 1 RS. Such reasoning has been endorsed for standard conflict tasks by several authors (Janczyk & Leuthold, 2018; Stürmer et al., 2002; Stürmer & Leuthold, 2003), suggesting that the automatic RA resulting from the irrelevant stimulus feature is suppressed after conflict (see Mayr & Keele, 2000, for the role of task inhibition in task switching, and Koch et al., 2010, for a review). In this case, we expect Task 2 diffusion model parameters being affected by type in Trial $n-1$, for example, revealing a smaller drift rate v following incompatible trials. (Of course, both scenarios are not mutually exclusive, and in the end, both might contribute to the observed effect.)

Analyses of the Task 2 **no-go BCE** data were run for Trial n go trials.[6] These data can help support our assumption that following go trials, participants remain in a preparatory state for the perhaps required Task 2 response. In particular, we expect shorter RT2s which may come together with a larger drift rate, a shorter non-decision time, and/or a smaller threshold separation. Modelling of the go/no-go Task 2 was the same as for the two-choice Task 2 of the compatibility-based BCE. Note, however, that the diffusion model was not developed for this type of task in the first place, and accordingly the results should be taken with additional caution (see Gomez, Ratcliff, & Perea, 2007, for more details and discussion).

A.2. Results

A.2.1. Behavioral results

All mean RT2s are visualized in Fig. A1 (see also Table A1 for the compatibility-based BCE and Table A2 for the no-go BCE) and ERs in Task 2 are summarized in Table A1 (compatibility-based BCE) and in Table A2 (no-go BCE).

For the **compatibility-based BCE**, the behavioral measures were analyzed as a function of type in Trial n and in Trial $n-1$ (similar to Task 1 analyses). The ANOVA for mean RT2s (1.31% outliers) of the compatibility-based BCE task yielded a significant main effect of type in Trial n, with on average 39 ms longer RT2s for incompatible (889 ms) as compared to compatible trials (850 ms), $F(1,47) = 31.67$, $p < .001$, $\eta_p^2 = 0.40$. RT2s were on average 10 ms shorter following incompatible (864 ms) than compatible (874 ms) trials, $F(1,47) = 6.25$, $p = .016$, $\eta_p^2 = 0.12$. Paralleling results for Task 1, a sequential modulation occurred, $F(1,47) = 269.40$, $p < .001$, $\eta_p^2 = 0.85$. Following compatible trials the BCE was present (143 ms), $t(47) = 5.71$, $p < .001$, $d = 0.82$, and following incompatible trials the BCE was inverted (−66 ms), $t(47) = -6.69$, $p < .001$, $d = -0.97$.

The ANOVA for ER2 revealed a significant main effect of type in Trial n, with on average 1.20% more errors for incompatible (4.71%) relative to compatible trials (3.51%), $F(1,47) = 8.20$, $p = .006$, $\eta_p^2 = 0.15$, indicating a BCE. ER2 was on average 0.83% higher following compatible (4.52%) relative to incompatible trials (3.69%), $F(1,47) = 8.41$, $p = .006$, $\eta_p^2 = 0.15$. The interaction was significant, $F(1,47) = 104.67$, $p < .001$, $\eta_p^2 = 0.69$, indicating a sequential modulation of the BCE. The BCE was present following compatible trials (4.45%), $t(47) = 3.31$, $p = .002$, $d = 0.48$, and it was inverted following incompatible trials (−2.05%), $t(47) = -3.77$, $p < .001$, $d = -0.54$.

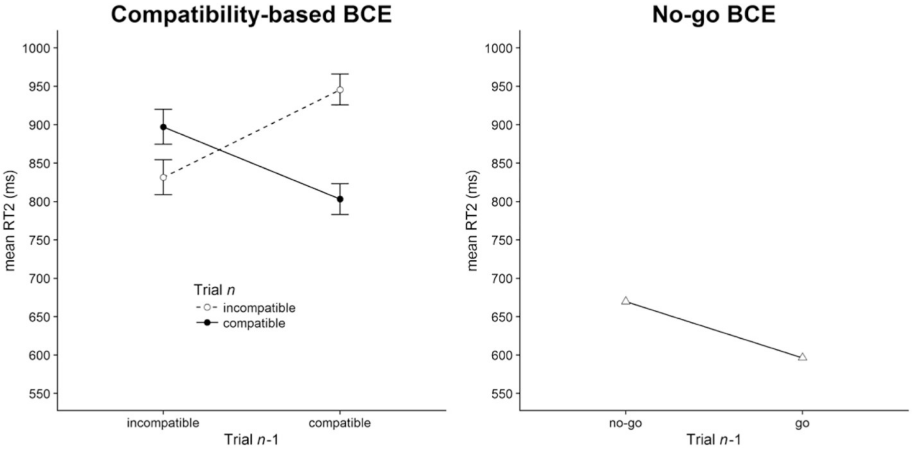

Fig. A1. Mean RTs of Task 2 as a function of type in Trial n (incompatible vs. compatible, compatibility-based BCE, left panel) and Trial $n-1$ (incompatible vs. compatible, or no-go vs. go) and task (compatibility-based BCE, left panel vs. no-go BCE, right panel). Errors bars are 95% within-subject confidence intervals for the difference between type in Trial n (see Pfister & Janczyk, 2013). Note, that for the no-go BCE only go trials were available in Trial n and, thus no error bars were calculated in this way.

Table A1
Mean RTs (in ms) and Error Rates (ER, in %) for Task 2 of the compatibility-based BCE task as a function of type in Trial n and Trial $n-1$ (in ms). Crosstalk effects were computed by subtracting values from compatible trials from those of incompatible trials of Trial n line-by-line. (Note: DV = dependent variable).

DV	Trial $n-1$	Trial n		
		Incompatible	Compatible	Crosstalk effect
RT	Incompatible	832	897	−65
	Compatible	946	803	143
ER	Incompatible	2.67	4.72	−2.05
	Compatible	6.75	2.30	4.45

For the **no-go BCE**, the ANOVA for mean RT2s (0.25% outliers) yielded a significant main effect of type in Trial $n-1$, with 74 ms longer RT2s

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[6] Additional analyses including Trial n go *and* no-go trials were run and the results did not differ qualitatively from the analyses reported here.

following no-go (670 ms) compared to go trials (596 ms), $F(1,47) = 120.19$, $p < .001$, $\eta_p^2 = 0.72$. ER2 was on average 1.36% larger for no-go (1.36%) relative to go trials (0.00%), $F(1,47) = 35.68$, $p < .001$, $\eta_p^2 = 0.43$. All other Fs ≤ 0.75, all other ps ≥ .391.

Table A2

Mean RTs (in ms) and Error Rates (ER, in %) for Task 2 of the no-go BCE task as a function of Trial n and Trial $n - 1$ (in ms). Crosstalk effects were computed by subtracting values from go trials from those of no-go trials of Trial n line-by-line. (Note: DV = dependent variable).

DV	Trial $n - 1$	Trial n		
		No-go	Go	Crosstalk effect
RT	No-go	–	670	–
	Go	–	596	–
ER	No-go	1.25	0.00	1.25
	Go	1.46	0.00	1.46

A.2.2. Diffusion model results

An illustration of the model fit for Task 2 of the **compatibility-based BCE** can be found in Fig. A2. Descriptive parameter data are visualized in Fig. A3 (see also Table A3).

For v, the main effect of type in Trial $n - 1$ was not significant, $F(1,47) = 0.34$, $p = .561$, $\eta_p^2 = 0.01$. The ANOVA for t_0 yielded a significant main effect of type in Trial $n - 1$, $F(1,47) = 26.02$, $p < .001$, $\eta_p^2 = 0.36$, with t_0 being on average 0.03 larger following incompatible (0.54) relative to compatible (0.51) trials. The ANOVA revealed that a was affected by type in Trial $n - 1$, $F(1,47) = 19.42$, $p < .001$, $\eta_p^2 = 0.29$, with a being on average 0.13 larger after compatible trials (1.71) relative to incompatible trials (1.58).

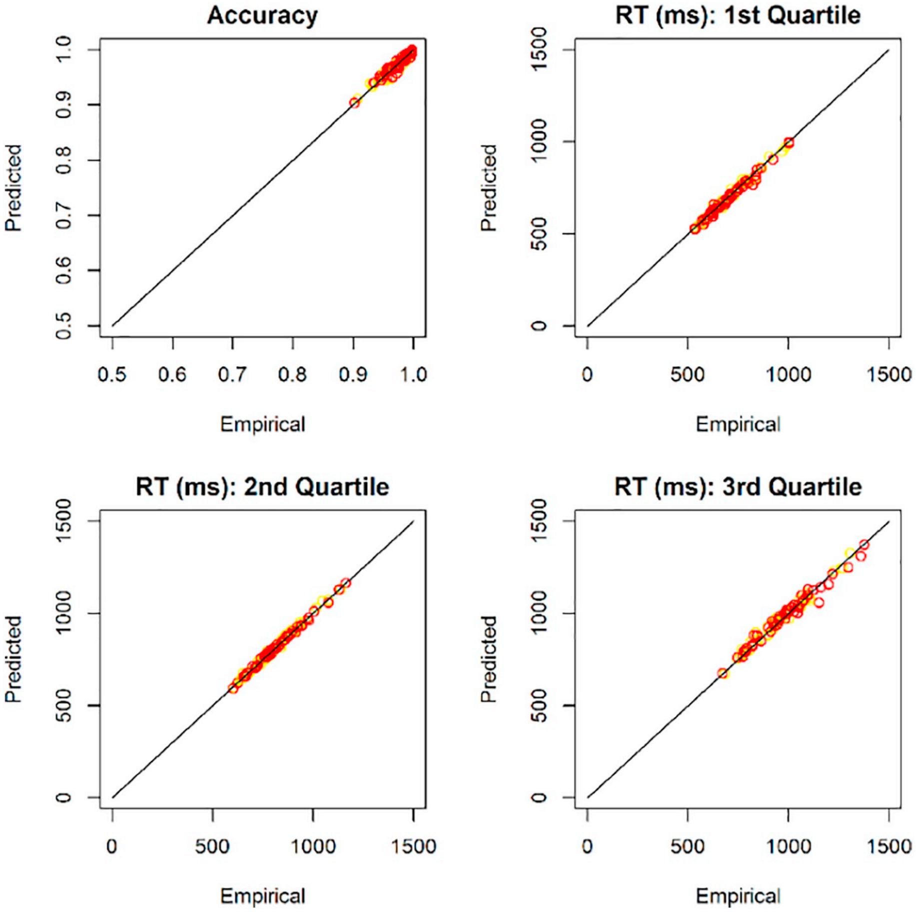

Fig. A2. Illustration of the model fit for the compatibility-based BCE Task 2: relationship between empirical and predicted statistics (accuracy, 1st, 2nd, and 3rd RT quartile). Red circles represent compatible Trials $n - 1$, and yellow circles represent incompatible Trials n means. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

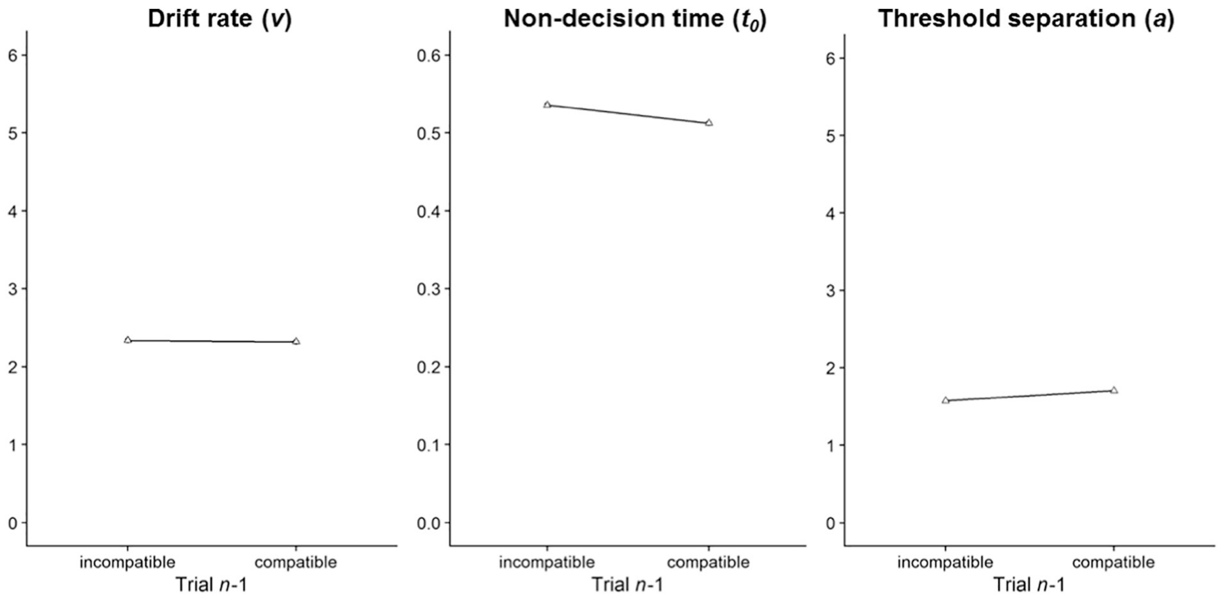

Fig. A3. Mean diffusion model parameter values of Task 2 of the compatibility-based BCE task as a function of type in Trial $n - 1$ (incompatible vs. compatible).

Table A3
Mean parameter values of drift rate (v), non-decision time (t_0), and threshold separation (a) for Task 2 of the compatibility-based BCE task as a function of type in Trial $n - 1$. (Note: DV = dependent variable).

DV	Trial $n - 1$	
	Incompatible	Compatible
v	2.34	2.32
t_0	0.54	0.51
a	1.58	1.71

An illustration of the model fit for Task 2 of the **no-go BCE** can be found in Fig. A4. Descriptive parameter data are visualized in Fig. A5 (see also Table A4).

The ANOVA for v yielded an on average 0.60 larger v following go (5.04) relative to no-go (4.44) trials, $F(1,47) = 5.78$, $p = .020$, $\eta_p^2 = 0.11$. Furthermore, the analysis for t_0 revealed a significant main effect of type in Trial $n - 1$, with an on average 0.07 larger t_0 following no-go (0.40) relative to go (0.33) trials $n - 1$, $F(1,47) = 40.08$, $p < .001$, $\eta_p^2 = 0.46$. Finally, the analysis revealed that a was unaffected by type in Trial $n - 1$, $F(1,47) = 2.50$, $p = .120$, $\eta_p^2 = 0.05$.

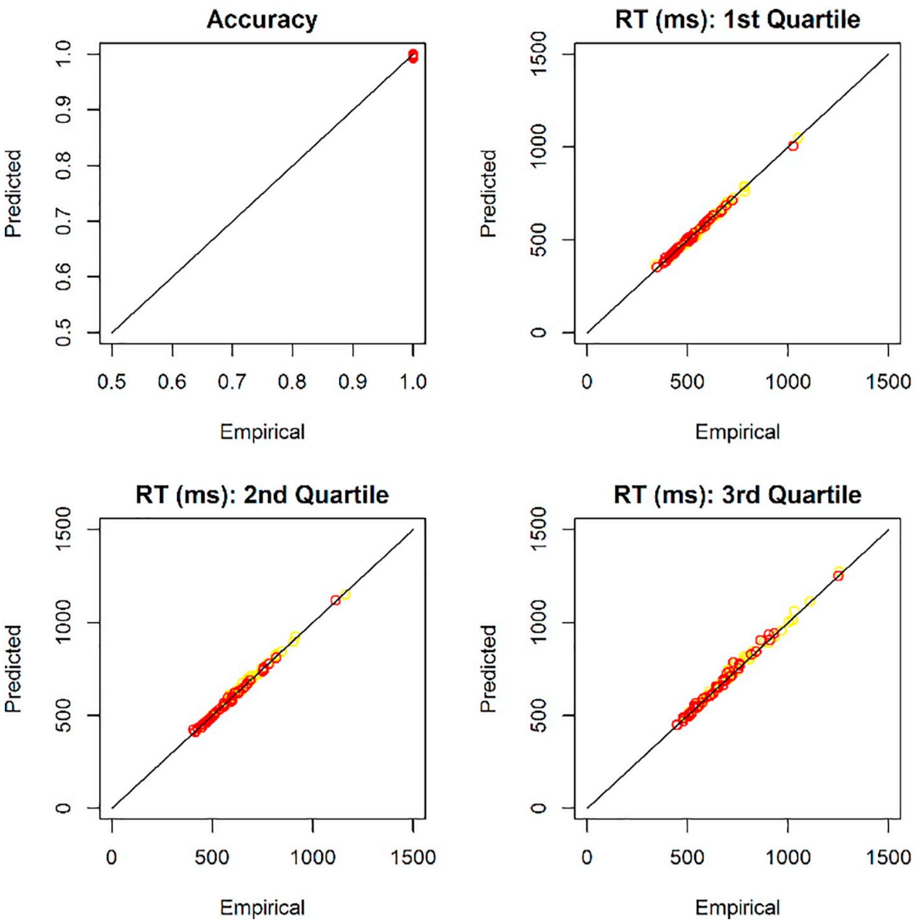

Fig. A4. Illustration of the model fit for the no-go BCE Task 2: relationship between empirical and predicted statistics (accuracy, 1st, 2nd, and 3rd RT quartile). Red circles represent go Trials $n - 1$, yellow circles represent no-go Trials $n - 1$ means. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

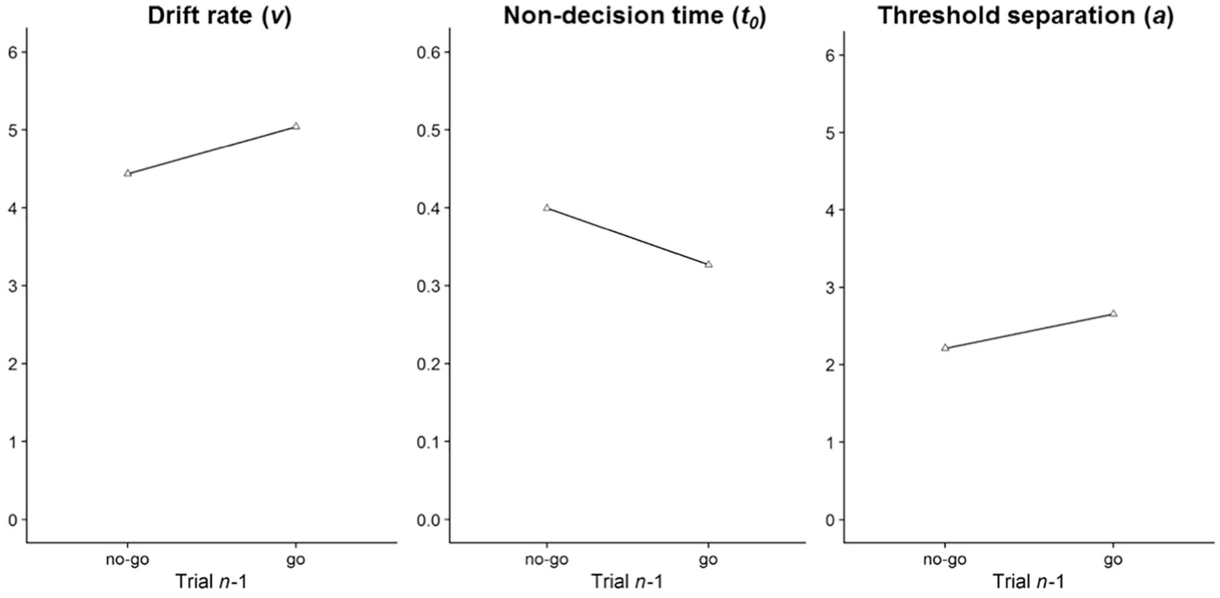

Fig. A5. Mean diffusion model parameter values of Task 2 of the no-go BCE task as a function of type in Trial $n - 1$ (no-go vs. go).

Table A4
Mean parameter values of drift rate (v), non-decision time (t_O), and threshold separation (a) for Task 2 of the no-go BCE task as a function of type in Trial $n-1$. (Note: DV = dependent variable).

DV	Trial $n-1$	
	No-go	Go
v	4.44	5.04
t_O	0.40	0.33
a	2.21	2.65

Reanalysis of Experiment 3 in Janczyk (2016). Task 2. An illustration of the model fit for Task 2 can be found in Fig. A6. Descriptive parameter data are visualized in Fig. A7 (see also Table A5). The ANOVA revealed that neither a, $F(1,31) = 1.89$, $p = .179$, $\eta_p^2 = 0.06$, nor v, $F(1,31) = 2.16$, $p = .152$, $\eta_p^2 = 0.07$, nor t_O, $F(1,31) = 0.60$, $p = .444$, $\eta_p^2 = 0.02$, were affected by Trial $n-1$.[7]

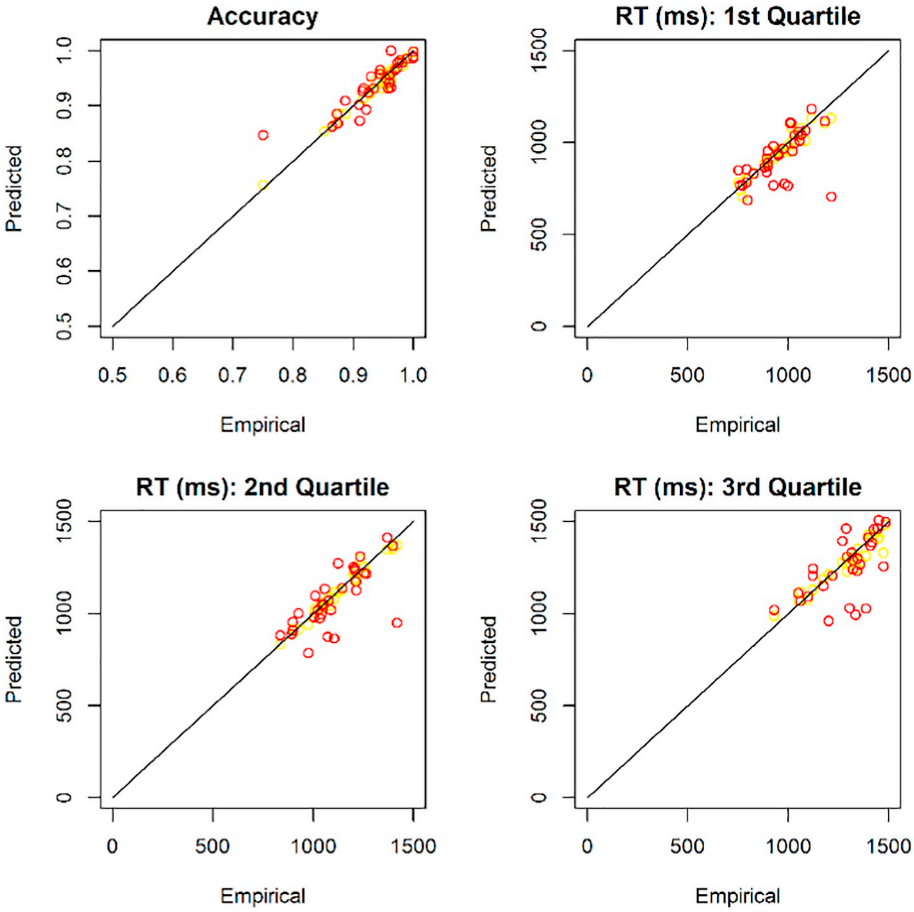

Fig. A6. Illustration of the model fit for the compatibility-based BCE Task 2 of the reanalysis of Janczyk (2016, Experiment 3): relationship between empirical and predicted statistics (accuracy, 1st, 2nd, and 3rd RT quartile). Red circles represent compatible Trials $n-1$, and yellow circles represent incompatible Trials n means. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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[7] Note, that v estimates for one participant were extraordinarily large. However, an exclusion of these data led to the qualitatively same results.

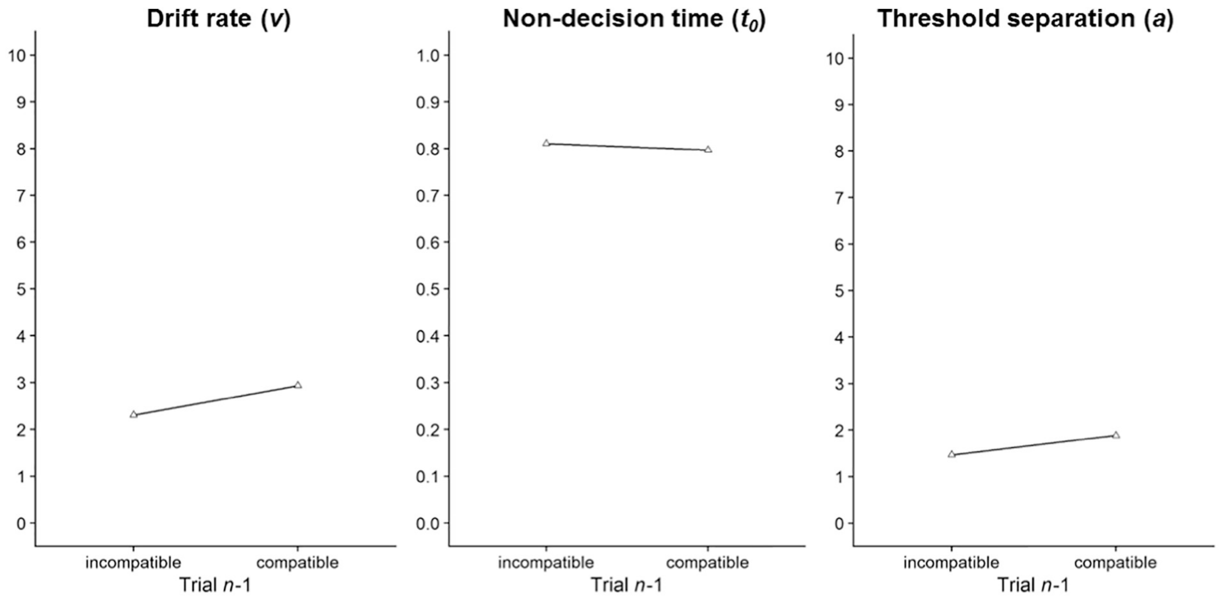

Fig. A7. Reanalysis of Janczyk (2016, Experiment 3). Mean diffusion model parameter values of Task 2 of the compatibility-based BCE task as a function of type in Trial $n-1$ (incompatible vs. compatible).

Table A5
Mean parameter values of, drift rate (v), non-decision time (t_0), and threshold separation (a) for Task 2 of the re-analysis of Janczyk (2016, Experiment 3) as a function of type in Trial $n-1$. (Note: DV = dependent variable).

DV	Trial $n-1$	
	Incompatible	Compatible
v	2.30	2.94
t_0	0.81	0.80
a	1.46	1.88

A.3. Discussion of Task 2 results

In the following we will briefly discuss Task 2 results, first for the compatibility-based BCE including the re-analysis of Janczyk (2016, Experiment 3), followed by the no-go BCE. A more detailed and integrative discussion of Task 2 results can be found in the General discussion.

A.3.1. Compatibility-based BCE task

v was unaffected by the compatibility of Trial $n-1$ in the data of the present study as well as in the reanalyzed data of Janczyk (2016) which indicates that the information uptake was *not* slowed following incompatible compared to compatible trials. This suggests that Task 2 RA was *not suppressed* following incompatible trials, but rather makes it more likely that Task 1 was shielded against influences of Task 2. t_0 was larger following incompatible than compatible Trials $n-1$, but it was not affected in the data of Janczyk (2016). We thus tentatively interpret results for t_0 as further evidence against suppression of Task 2 RA and in favor of shielding of Task 1.

A.3.2. No-go BCE task

For Task 2, RTs were shorter following go than no-go trials and drift rate was larger following go than no-go trials, in line with an increased Task 2 preparation following go trials. Furthermore, t_0 was smaller following go relative to no-go trials. This is in line with the idea that the motor programming acquired in the previous trial was still active (Rosenbaum et al., 1986). Taken together, results for Task 2 suggest that cognitive control in the no-go BCE task is adjusted via preparation for Task 2.

References

Bissett, P. G., & Logan, G. D. (2011). Balancing cognitive demands: Control adjustments in the stop-signal paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 37*, 392–404.

Botvinick, M. M. (2007). Conflict monitoring and decision-making: Reconciling two perspectives on anterior cingulate function. *Cognitive, Affective, & Behavioral Neuroscience, 7*, 356–366.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108*, 624–652.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Erlbaum.

Donders, F. C. (1969). On the speed of mental processes. *Acta Psychologica, 30*, 412–431.

Donkers, F. C. L., & van Boxtel, G. J. M. (2004). The N2 in go/no-go tasks reflects conflict monitoring not response inhibition. *Brain and Cognition, 56*, 165–176.

Dreisbach, G., & Fischer, R. (2015). Conflicts as aversive signals for control adaptation. *Current Directions in Psychological Science, 24*, 255–260.

Dreisbach, G., & Haider, H. (2008). That's what task sets are for: Shielding against irrelevant information. *Psychological Research, 72*, 355–361.

Dreisbach, G., & Haider, H. (2009). How task representations guide attention: Further evidence for the shielding function of task sets. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35*, 477–486.

Durst, M., & Janczyk, M. (2018). The motor locus of no-go backward crosstalk. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 44*(12), 1931–1946.

Egner, T. (2007). Congruency sequence effects and cognitive control. *Cognitive, Affective,*

& Behavioral Neuroscience, 7, 380–390.

Ellenbogen, R., & Meiran, N. (2008). Working memory involvement in dual-task performance: Evidence from the backward compatibility effect. *Memory & Cognition, 36*, 968–978.

Ellenbogen, R., & Meiran, N. (2011). Objects and events as determinants of parallel processing in dual tasks: Evidence from the backward compatibility effect. *Journal of Experimental Psychology: Human Perception and Performance, 37*(1), 152.

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Attention, Perception, & Psychophysics, 16*, 143–149.

Fischer, R., Gottschalk, C., & Dreisbach, G. (2014). Context-sensitive adjustment of cognitive control in dual-task performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*, 399–416.

Fischer, R., & Plessow, F. (2015). Efficient multitasking: Parallel versus serial processing of multiple tasks. *Frontiers in Psychology, 6*, 1366.

Germar, M., Schlemmer, A., Krug, K., Voss, A., & Mojzisch, A. (2014). Social influence and perceptual decision making: A diffusion model analysis. *Personality and Social Psychology Bulletin, 40*, 217–231.

Gomez, P., Ratcliff, R., & Childers, R. (2015). Pointing, looking at, and pressing keys: A diffusion model account of response modality. *Journal of Experimental Psychology: Human Perception and Performance, 41*, 1515–1523.

Gomez, P., Ratcliff, R., & Perea, M. (2007). A model of the go/no-go task. *Journal of Experimental Psychology: General, 136*(3), 389–413.

Goschke, T. (2003). Voluntary action and cognitive control from a cognitive neuroscience perspective. In S. Maasen, W. Prinz, & G. Roth (Eds.). *Voluntary action: Brains, minds, and sociality* (pp. 49–85). New York: Oxford University Press.

Gratton, G., Coles, M. G., & Donchin, E. (1992). Optimizing the use of information: Strategic control of activation of responses. *Journal of Experimental Psychology: General, 121*, 480–506.

Hommel, B. (1998). Automatic stimulus–response translation in dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 1368–1384.

Hommel, B., & Eglau, B. (2002). Control of stimulus-response translation in dual-task performance. *Psychological Research, 66*, 260–273.

Janczyk, M. (2013). Level 2 perspective taking entails two processes: Evidence from PRP experiments. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 39*, 1878–1887.

Janczyk, M. (2016). Sequential modulation of backward crosstalk and task-shielding in dual-tasking. *Journal of Experimental Psychology: Human Perception and Performance, 42*, 631–647.

Janczyk, M. (2017). A common capacity limitation for response and item selection in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 43*, 1690–1698.

Janczyk, M., Büschelberger, J., & Herbort, O. (2017). Larger between-task crosstalk in children than in adults: Behavioral results from the backward crosstalk paradigm and a diffusion model analysis. *Journal of Experimental Child Psychology, 155*, 95–112.

Janczyk, M., & Huestegge, L. (2017). Effects of a no-go task 2 on task 1 performance in dual-tasking: From benefits to costs. *Attention, Perception, & Psychophysics, 79*, 796–806.

Janczyk, M., & Lerche, V. (2018). A diffusion model analysis of the response-effect compatibility effect. *Journal of Experimental Psychology: General*. https://doi.org/10.1037/xge0000430 Advance online publication.

Janczyk, M., & Leuthold, H. (2018). Effector system-specific sequential modulations of congruency effects. *Psychonomic Bulletin & Review, 25*, 1066–1072.

Janczyk, M., Mittelstädt, P., & Wienrich, C. (2018). Parallel dual-task processing and task-shielding in older and younger adults: Behavioral and diffusion model results. *Experimental Aging Research, 44*, 95–116.

Janczyk, M., Pfister, R., Hommel, B., & Kunde, W. (2014). Who is talking in backward crosstalk? Disentangling response-from goal-conflict in dual-task performance. *Cognition, 132*, 30–43.

Janczyk, M., Pfister, R., Wallmeier, G., & Kunde, W. (2014). Exceptions to the PRP effect? A comparison of prepared and unconditioned reflexes. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*, 776.

Janczyk, M., Renas, S., & Durst, M. (2018). Identifying the locus of compatibility-based backward crosstalk: Evidence from an extended PRP paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 44*, 261–276.

Kerns, J. G., Cohen, J. D., MacDonald, A. W. I. I. I., Cho, R. Y., Stenger, V. A., & Carter, C. S. (2004). Anterior cingulate conflict monitoring and adjustments in control. *Science, 303*, 1023–1026.

Ko, Y.-T., & Miller, J. (2014). Locus of backward crosstalk effects on task 1 in a psychological refractory period task. *Experimental Psychology, 61*, 30–37.

Koch, I., Gade, M., Schuch, S., & Philipp, A. M. (2010). The role of inhibition in task switching: A review. *Psychonomic Bulletin & Review, 17*, 1–14.

Kunde, W., Pfister, R., & Janczyk, M. (2012). The locus of tool-transformation costs. *Journal of Experimental Psychology: Human Perception and Performance, 38*, 703–714.

Lehle, C., & Hübner, R. (2009). Strategic capacity sharing between two tasks: Evidence from tasks with the same and with different task sets. *Psychological Research, 73*, 707–726.

Lehle, C., Steinhauser, M., & Hübner, R. (2009). Serial or parallel processing in dual tasks: What is more effortful? *Psychophysiology, 46*, 502–509.

Leotti, L. A., & Wager, T. D. (2010). Motivational influences on response inhibition measures. *Journal of Experimental Psychology: Human Perception and Performance, 36*, 430–447.

Lerche, V., & Voss, A. (2016). Model complexity in diffusion modeling: Benefits of making the model more parsimonious. *Frontiers in Psychology, 7*, 1324.

Lerche, V., & Voss, A. (2017). Experimental validation of the diffusion model based on a slow response time paradigm. *Psychological Research*. https://doi.org/10.1007/s00426-017-0945-8 Advance online publication.

Levy, J., & Pashler, H. (2008). Task prioritisation in multitasking during driving: Opportunity to abort a concurrent task does not insulate braking responses from dual-task slowing. *Applied Cognitive Psychology, 22*, 507–525.

Liddle, E. B., Scerif, G., Hollis, C. P., Batty, M. J., Groom, M. J., Liotti, M., & Liddle, P. F. (2009). Looking before you leap: A theory of motivated control of action. *Cognition, 112*, 141–158.

Lien, M.-C., & Proctor, R. W. (2000). Multiple spatial correspondence effects on dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 26*, 1260–1280.

Lien, M.-C., & Proctor, R. W. (2002). Stimulus-response compatibility and psychological refractory period effects: Implications for response selection. *Psychonomic Bulletin & Review, 9*, 212–238.

Lien, M.-C., Ruthruff, E., Hsieh, S., & Yu, Y. T. (2007). Parallel central processing between tasks: Evidence from lateralized readiness potentials. *Psychonomic Bulletin & Review, 14*, 133–141.

Logan, G. D., & Delheimer, J. A. (2001). Parallel memory retrieval in dual-task situations: II. Episodic memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27*, 668.

Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review, 108*, 393.

Logan, G. D., & Schulkind, M. D. (2000). Parallel memory retrieval in dual-task situations: I. Semantic memory. *Journal of Experimental Psychology: Human Perception and Performance, 26*, 1072.

Mayr, U., & Keele, S. W. (2000). Changing internal constraints on action: The role of backward inhibition. *Journal of Experimental Psychology: General, 129*, 4–26.

Miller, J. (2006). Backward crosstalk effects in psychological refractory period paradigms: Effects of second-task response types on first-task response latencies. *Psychological Research, 70*, 484–493.

Miller, J. (2017). Psychophysiological measurement of backward response activation in the prioritized processing paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 43*(5), 941–953.

Miller, J., & Alderton, M. (2006). Backward response-level crosstalk in the psychological refractory period paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 32*, 149.

Miller, J., & Durst, M. (2014). “Just do it when you get a chance”: The effects of a background task on primary task performance. *Attention, Perception, & Psychophysics, 76*, 2560–2574.

Miller, J., & Durst, M. (2015). A comparison of the psychological refractory period and prioritized processing paradigms: Can the response-selection bottleneck model explain them both? *Journal of Experimental Psychology: Human Perception and Performance, 41*, 1420–1441.

Miller, J., & Reynolds, A. (2003). The locus of redundant-targets and nontargets effects: Evidence from the psychological refractory period paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 1126–1142.

Mittelstädt, V., & Miller, J. (2017). Separating limits on preparation versus online processing in multitasking paradigms: Evidence for resource models. *Journal of Experimental Psychology: Human Perception and Performance, 43*, 89–102.

Naefgen, C., Caissie, A. F., & Janczyk, M. (2017). Stimulus-response links and the backward crosstalk effect—A comparison of forced-and free-choice tasks. *Acta Psychologica, 177*, 23–29.

Naefgen, C., Dambacher, M., & Janczyk, M. (2018). Why free choices take longer than forced choices: Evidence from response threshold manipulations. *Psychological Research, 82*, 1039–1052.

Navon, D., & Miller, J. (2002). Queuing or sharing? A critical evaluation of the single-bottleneck notion. *Cognitive Psychology, 44*, 193–251.

Nieuwenhuis, S., Yeung, N., van den Wildenberg, W., & Ridderinkhof, K. R. (2003). Electrophysiological correlates of anterior cingulate function in a go/no-go task: Effects of response conflict and trial type frequency. *Cognitive, Affective, & Behavioral Neuroscience, 3*, 17–26.

Notebaert, W., Gevers, W., Verbruggen, F., & Liefooghe, B. (2006). Top-down and bottom-up sequential modulations of congruency effects. *Psychonomic Bulletin & Review, 13*, 112–117.

Oriet, C., Tombu, M., & Jolicoeur, P. (2005). Symbolic distance affects two processing loci in the number comparison task. *Memory & Cognition, 33*, 913–926.

Pashler, H. (1984). Processing stages in overlapping tasks: Evidence for a central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance, 10*, 358–377.

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin, 116*, 220–244.

Pashler, H., Johnston, J. C., & Ruthruff, E. (2001). Attention and performance. *Annual Review of Psychology, 52*, 629–651.

Pfister, R., & Janczyk, M. (2013). Confidence intervals for two sample means: Calculation, interpretation, and a few simple rules. *Advances in Cognitive Psychology, 9*, 74–80.

Praamstra, P., Kleine, B. U., & Schnitzler, A. (1999). Magnetic stimulation of the dorsal premotor cortex modulates the Simon effect. *Neuroreport, 10*, 3671–3674.

Ratcliff, R. (1978). A theory of memory retrieval. *Psychological Review, 85*, 59–108.

Ratcliff, R., Smith, P. L., Brown, S. D., & McKoon, G. (2016). Diffusion decision model: Current issues and history. *Trends in Cognitive Sciences, 20*, 260–281.

Ratcliff, R., Thapar, A., & McKoon, G. (2011). Effects of aging and IQ on item and associative memory. *Journal of Experimental Psychology: General, 140*, 464–487.

Renas, S., Durst, M., & Janczyk, M. (2018). Action effect features, but not anatomical features, determine the backward crosstalk effect: Evidence from crossed-hands experiments. *Psychological Research, 82*, 970–980.

Rosenbaum, D. A., Weber, R. J., Hazelett, W. M., & Hindorff, V. (1986). The parameter remapping effect in human performance: Evidence from tongue twisters and finger fumblers. *Journal of Memory and Language, 25*, 710.

Röttger, E., & Haider, H. (2017). Investigating the characteristics of "not responding": Backward crosstalk in the PRP paradigm with forced vs. free no-go decisions. *Psychological Research, 81*, 596–610.

Ruiz Fernández, S., & Ulrich, R. (2010). Late backward effects in the refractory period paradigm: Effects of task 2 execution on task 1 performance. *Psychological Research, 74*, 378–387.

Saunders, B., Lin, H., Milyavskaya, M., & Inzlicht, M. (2017). The emotive nature of conflict monitoring in the medial prefrontal cortex. *International Journal of Psychophysiology, 119*, 31–40.

Scherbaum, S., Gottschalk, C., Dshemuchadse, M., & Fischer, R. (2015). Action dynamics in multitasking: The impact of additional task factors on the execution of the prioritized motor movement. *Frontiers in Psychology, 6*.

Schmitz, F., & Voss, A. (2012). Decomposing task-switching costs with the diffusion model. *Journal of Experimental Psychology: Human Perception and Performance, 38*, 222.

Schubert, A.-L., Hagemann, D., Voss, A., Schankin, A., & Bergmann, K. (2015). Decomposing the relationship between mental speed and mental abilities. *Intelligence, 51*, 28–46.

Schubert, T., Fischer, R., & Stelzel, C. (2008). Response activation in overlapping tasks and the response-selection bottleneck. *Journal of Experimental Psychology: Human Perception and Performance, 34*, 376–397.

Schuch, S., Dignath, D., Steinhauser, M., & Janczyk, M. (2018). Monitoring and control in multitasking. *Psychonomic Bulletin & Review*. https://doi.org/10.3758/s13423-018-1512-z Advance online publication.

Schweickert, R. (1978). A critical path generalization of the additive factor method: Analysis of a stroop task. *Journal of Mathematical Psychology, 18*, 105–139.

Serfas, B. G., Florack, A., Büttner, O. B., & Voegeding, T. (2017). What does it take for sour grapes to remain sour? Persistent effects of behavioral inhibition in go/no-go tasks on the evaluation of appetitive stimuli. *Motivation Science, 3*, 1–18.

Stelzel, C., Brandt, S. A., & Schubert, T. (2009). Neural mechanisms of concurrent stimulus processing in dual tasks. *NeuroImage, 48*, 237–248.

Strayer, D. L. D., & Drews, F. A. (2004). Profiles in driver distraction: Effects of cell phone conversations on younger and older drivers. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 46*, 640–649.

Strayer, D. L., & Drews, F. A. (2007). Cell-phone–induced driver distraction. *Current Directions in Psychological Science, 16*, 128–131.

Stürmer, B., & Leuthold, H. (2003). Control over response priming in visuomotor processing: A lateralized event-related potential study. *Experimental Brain Research, 153*, 35–44.

Stürmer, B., Leuthold, H., Soetens, E., Schröter, H., & Sommer, W. (2002). Control over location-based response activation in the Simon task: Behavioral and electrophysiological evidence. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 1345–1363.

Thomson, S. J., Danis, L. K., & Watter, S. (2015). PRP training shows task 1 response selection is the locus of the backward response compatibility effect. *Psychonomic Bulletin & Review, 22*, 212–218.

Thomson, S. J., & Watter, S. (2013). Information continuity across the response selection bottleneck: Early parallel task 2 response activation contributes to overt task 2 performance. *Attention, Perception, & Psychophysics, 75*, 934–953.

Tombu, M., & Jolicœur, P. (2003). A central capacity sharing model of dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 3–18.

Ulrich, R., Schröter, H., Leuthold, H., & Birngruber, T. (2015). Automatic and controlled stimulus processing in conflict tasks: Superimposed diffusion processes and delta functions. *Cognitive Psychology, 78*, 148–174.

Verbruggen, F., & Logan, G. D. (2008). Automatic and controlled response inhibition: Associative learning in the go/no-go and stop-signal paradigms. *Journal of Experimental Psychology: General, 137*, 649–672.

Voss, A., Nagler, M., & Lerche, V. (2013). Diffusion models in experimental psychology: A practical introduction. *Experimental Psychology, 60*, 385–402.

Voss, A., Rothermund, K., & Brandtstädter, J. (2008). Interpreting ambiguous stimuli: Separating perceptual and judgmental biases. *Journal of Experimental Social Psychology, 44*, 1048–1056.

Voss, A., Rothermund, K., & Voss, J. (2004). Interpreting the parameters of the diffusion model: An empirical validation. *Memory & Cognition, 32*, 1206–1220.

Voss, A., & Voss, J. (2007). Fast-dm: A free program for efficient diffusion model analysis. *Behavior Research Methods, 39*, 767–775.

Voss, A., Voss, J., & Lerche, V. (2015). Assessing cognitive processes with diffusion model analyses: A tutorial based on fast-dm-30. *Frontiers in Psychology, 6*, 336.

Watter, S., & Logan, G. D. (2006). Parallel response selection in dual-task situations. *Perception & Psychophysics, 68*, 254–277.

Welford, A. T. (1952). The 'psychological refractory period' and the timing of high-speed performance—A review and a theory. *British Journal of Psychology. General Section, 43*, 2–19.

Wessel, J. R., & Aron, A. R. (2013). Unexpected events induce motor slowing via a brain mechanism for action-stopping with global suppressive effects. *The Journal of Neuroscience, 33*, 18481–18491.

Wessel, J. R., & Aron, A. R. (2017). On the globality of motor suppression: Unexpected events and their influence on behavior and cognition. *Neuron, 93*, 259–280.

Wühr, P. (2004). Sequential modulations of logical-recoding operations in the Simon task. *Experimental Psychology, 51*, 98–108.

10.4 Study 4

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RUNNING HEAD: Two types of compatibility-based backward crosstalk

Two different types of compatibility-based backward crosstalk in dual-tasks

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Abstract

A frequent observation in dual-task experiments is that performance of Task 1 is influenced by its dimensional overlap with features of Task 2. Such compatibility-based backward crosstalk effects (BCEs) occur when dimensional overlap exists between the responses in the two tasks – the R1-R2 BCE – or between the stimulus in Task 1 and the response in Task 2 – the S1-R2 BCE. The present study investigated whether the two BCEs have a common processing locus or different ones. To this end, Experiment 1 used the additive factors method and excluded a perceptual locus for both BCEs. To further investigate whether the two BCEs are based on the same or different capacity-limited processes, Experiment 2 and 3 examined sequential modulations within and across the two BCEs. Since no such sequential modulations across the two BCEs were observed in these experiments, the two BCEs are likely based on two different and presumably subsequent capacity-limited processes.

Keywords: dual-task; backward crosstalk; sequential modulation; Psychological Refractory Period; compatibility

Statement of public significance

Humans often multitask, that is, they perform more than one task simultaneously. Interestingly, characteristics of Task 2 can influence processing of Task 1, in particular when they share common features between stimuli and/or responses. Two instances of such effects are known, one involving the relation between the two responses in Task 1 and 2, the other involving the Task 1 stimulus and the response in Task 2. The results of the present study suggest that both need to be carefully distinguished. Additionally, because both types of crosstalk are caused by capacity-limited processes, any performance decrements propagate to other subsequent tasks as well. These results are of interest for human multitasking research in general and for applied fields like human factors.

Two different types of compatibility-based backward crosstalk in dual-tasks

One of the central debates in dual-task research concerns whether humans are able to perform two tasks simultaneously, or whether certain parts of the two tasks can only be carried out one after the other in a serial fashion. According to the latter view, perceptual and motor stages of two tasks can run in parallel, whereas the central stage of cognitive processing can only serve one task at any point in time. Thus, the second of two subsequently performed tasks has to wait in order to gain access to this capacity-limited stage (for exceptions, see Janczyk, Pfister, Wallmeier, & Kunde, 2014) and this waiting time is known as the cognitive slack. A widely accepted model assumes that the serial capacity-limited central stage is response selection, and thus has been termed the *response selection bottleneck* (RSB) *model* (Pashler, 1994; Welford, 1952). Nevertheless, some evidence contradicting the notion of strictly serial processing has accumulated in the last years. A particularly crucial piece of evidence is the backward crosstalk effect (BCE), that is, the observation that certain aspects of Task 2 already influence performance in Task 1. This implies that the processes related to response selection in the two tasks are not entirely isolated from each other.

Two types of compatibility-based BCEs. A compatibility-based BCE was first reported by Hommel (1998), who observed that RTs in Task 1 were shorter when certain task features of Task 1 were compatible with features of Task 2. Nowadays, it is important to distinguish between two types of such BCEs. First, a BCE can be observed when a (spatial) overlap between the responses of Task 1 (R1) and Task 2 (R2) exists – the R1-R2 BCE (Janczyk, Pfister, Hommel, & Kunde, 2014; Lien & Proctor, 2000; Watter & Logan, 2006; Thomson, Watter, & Finkelshtein, 2010; Miller & Durst, 2014, 2015). Second, a BCE can also be obtained when the Stimulus in Task 1 (S1) conceptually overlaps with R2 – the S1-R2 BCE (Hommel & Eglau, 2002; Ellenbogen & Meiran, 2008; Lien, Ruthruff, Hsieh & Yu, 2007).

As mentioned above, the R1-R2 BCE results from dimensional overlap of the two responses on each given trial. For example, in Experiment 1 of Hommel (1998), participants were presented with colored letters, and instructed to respond to the color of the letter with a left versus right manual keypress and to respond to the identity of the letter by vocally uttering the word “left” versus “right”. When both responses were spatially compatible (e.g., a left manual keypress and a vocal “left” utterance), RTs of Task 1 (RT1s) were shorter than when both responses were spatially incompatible (e.g., a left manual keypress and a vocal “right” utterance). Several studies replicated the R1-R2 BCE with spatial overlap between two manual responses (Janczyk et al., 2014; Lien & Proctor, 2000; Watter & Logan, 2006; Thomson et al., 2010; Miller & Durst, 2014, 2015), manual and pedal responses (Janczyk, 2016; Durst & Janczyk, 2019), and vocal and manual responses (Renas, Durst, & Janczyk, 2018).

In further experiments, Hommel (1998) changed the instructions for Task 2. Now, participants were instructed to respond to the identity of the letter with the vocal utterance “rot” (German for “red”) versus “grün” (German for “green”). When S1 and R2 were conceptually compatible (e.g., a red letter and the utterance “rot”) RT1s were shorter relative to when S1 and R2 were conceptually incompatible (e.g., a red letter and the utterance “grün”). This S1-R2 BCE has yet received relatively little attention in the literature. Only a few other studies reported instances of S1-R2 BCEs with conceptual overlap between the color of S1 and a vocal R2 (Hommel & Eglau, 2002; Ellenbogen & Meiran, 2008) and spatial overlap between an auditory S1 and a manual R2 (Lien, Ruthruff, Hsieh & Yu, 2007).

In sum, two types of compatibility-based BCEs can be conceptually distinguished: Compatibility in the R1-R2 BCE depends on overlap between the two responses, whereas the S1-R2 BCE depends on dimensional overlap between S1 and R2.

Theoretical explanations for compatibility-based BCEs. To account for these BCEs, some authors made the additional assumption of a capacity-unlimited stage of response activation that immediately follows the perceptual stage and can run in parallel with all other stages (Hommel, 1998; Lien & Proctor, 2002). When the temporal overlap of the two tasks is sufficiently high (i.e., at a short stimulus onset asynchrony, SOA), response activation from

Task 2 can influence that of Task 1, resulting in a BCE (Hommel, 1998; Janczyk, 2016). According to this view, response activation is the *locus* of the compatibility-based BCEs.

In contrast, recent studies identified the locus of the R1-R2 compatibility-based BCE in the capacity-limited central stage of Task 1 (Janczyk et al., 2018; Thomson, Danis, & Watter, 2015). According to this alternative view, response activation in Task 2 directly affects the central capacity-limited stage of response selection in Task 1. Important for the present study, Janczyk et al. also obtained evidence that the S1-R2 BCE requires capacity-limited processing similar to the R1-R2 BCE, even though – at first glance – the nature of the S1-R2 BCE rather suggests a perceptual locus of the effect. However, the results by Janczyk et al. (Experiment 3) exhibited a descriptive trend that would actually be consistent with a perceptual locus of the S1-R2 BCE.[1]

The present study. The present three experiments aim to clarify whether the R1-R2 BCE and the S1-R2 BCE share a common processing locus. Experiment 1 was run to further investigate the possibility of a perceptual locus of the S1-R2 BCE (see Experiment 3 of Janczyk et al., 2018). To anticipate, the results did not support this possibility. Together with the results of Janczyk et al. it then appears that both BCEs have a locus in the capacity-limited stage of central processing. However, this does not necessarily mean that both BCEs involve the same processes, and arguably, the conceptual differences between the two BCEs cast doubt on that. This question was addressed in Experiments 2 and 3 by means of sequential modulations within and across the two types of BCEs. We will come back to this in more detail in the introduction to Experiment 2.

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[1] Janczyk et al. (2018) applied the locus of slack logic in an extended PRP paradigm comprising three instead of two tasks (Experiments 1-3). Task 1 was an unrelated binary tone discrimination task, while spatial or conceptual overlap was manipulated between Task 2 and 3, thus resulting in a BCE in Task 2. Following the locus of slack logic, an underadditive interaction of SOA and the BCE in Task 2 indicates that the BCE has its locus in a precentral stage, such as response activation. Additive effects of SOA and the BCE, however, would indicate a locus of the BCE at earliest in the capacity-limited central stage. While all experiments revealed additive effects of SOA and the BCE, a descriptive trend towards underadditivity was observed in Experiment 3, where conceptual overlap between S2 and R3 was realized. This leaves open the possibility of a precentral locus of the S2-R3 BCE.

Experiment 1

This experiment was run to further rule out a perceptual locus of the S1-R2 BCE. To this end, participants performed separate blocks of R1-R2 BCE and S1-R2 BCE tasks. In both types of blocks, we varied the brightness of S1 on a trial-by-trial basis – a manipulation affecting the perceptual stage (see Pashler & Johnston, 1989). We expected shorter RT1s for bright compared with dark S1s, and R1-R2 and S1-R2 BCEs in the respective blocks. The crucial predictions rely on Sternberg's (1969) additive factors logic. This logic predicts an interaction of two experimental factors if they affect the same processing stage. In contrast, additive effects of two factors are consistent with different processing loci. As the available evidence strongly suggests that the R1-R2 BCE has its locus in the central stage (Janczyk et al., 2018; Thomson et al., 2015), it should yield an additive effect with S1 brightness. For the S1-R2 BCE, however, the trend towards underadditivity in Experiment 3 of Janczyk et al. (2018) leaves open the possibility of a perceptual locus. In this case, an interaction of the S1-R2 BCE with S1 brightness is expected. Additionally, one would also expect a three-way interaction between S1 brightness and the two types of BCEs. In contrast, if the S1-R2 BCE has its locus in the capacity-limited central stage as well as the R1-R2 BCE, the S1-R2 BCE should have an additive effect with S1 brightness, and the three-way interaction should not be significant.

Method

Participants. Fourty-eight students[2] (34 female) from the University of Tübingen, aged 19 to 45 years (*M* = 23.6 years, *SD* = 5.11), participated for monetary compensation (8€) or course credit. All participants provided written informed consent before the experiment and had normal or corrected-to-normal vision.

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[2] The critical result is a two-way interaction between compatibility relation and S1 brightness. We conducted a power analysis for this interaction assuming a medium effect size with $\alpha = .05$ and $1 - \beta = .9$. This analysis yielded a minimum sample size of $n = 44$.

Apparatus and stimuli. A standard PC was used for stimulus presentation and response collection. Stimuli and instructions were presented on a 17-in. CRT monitor. Stimuli were the letters “H” or “S” surrounded by a frame colored in red or green, presented in the center of an otherwise black screen. The color of the frame served as S1 and was either bright or dark. The identity of the letter served as S2. R1s were given manually via two response keys, one to the left and one to the right of the participant. R2s were vocal utterances.

Task and procedure. The trial structure and the tasks are illustrated in Figure 1. Task 1 was to respond to S1 with a manual key-press of the left or right index finger (R1), and Task 2 was to respond to S2 with a vocal utterance (R2). In R1-R2 BCE blocks, R2 was the vocal utterance “links” or “rechts” (German for “left” and “right”). In S1-R2 BCE blocks, R2 was the vocal utterance “rot” or “grün” (German for “red” and “green”). The S-R mappings of both tasks were counterbalanced across participants.

Each trial started with a white fixation cross (250 ms), followed by a blank screen (250 ms). Then, the letter surrounded by a bright or dark colored frame was presented at the center of the screen for a maximum of 4,000 ms or until both responses were registered. The next trial started after an inter-trial interval (ITI) of 1000 ms. In case of an error, a respective feedback message was presented on the screen for 1,000 ms before the ITI.

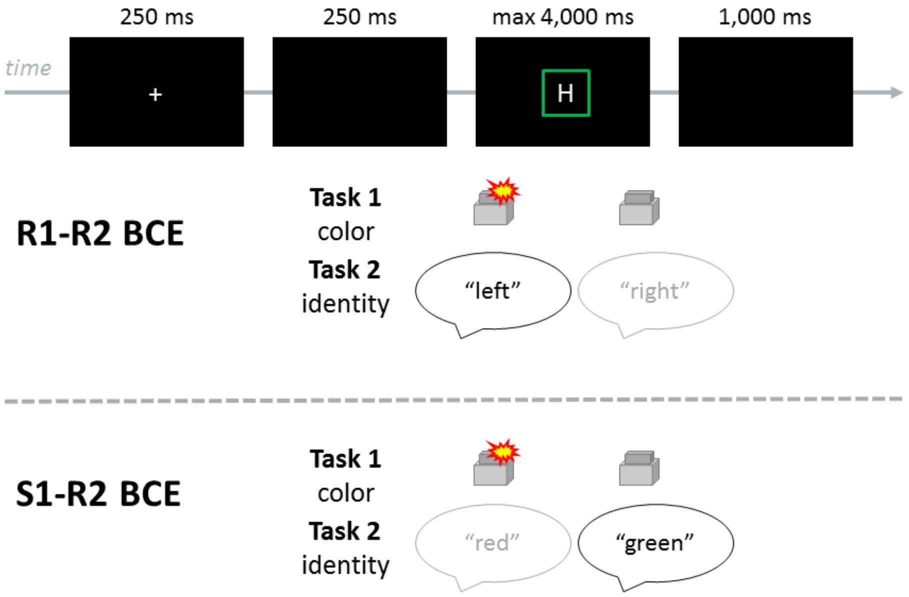

Figure 1. Trial structure and tasks of the two different block types in Experiment 1. In each trial, participants first responded to the color of the frame in a manual two-choice task by pressing a left or right key (Task 1). Then, participants responded to the identity of the letter in a vocal two-choice task (Task 2). In R1-R2 blocks, the responses were the words "left" and "right", and in S1-R2 blocks, they were "red" and "green". In the depicted example, Stimulus 1 is a green frame which requires a left index finger response in Task 1. In Task 2 of R1-R2 blocks, the identity "H" requires a vocal utterance of the word "left", while the letter "S" indicates a "right" utterance. In this trial, the R1-R2 relation is compatible. In Task 2 of S1-R2 blocks, the identity "H" requires a vocal utterance of the word "green", while the letter "S" indicates a "red" utterance. In this trial, the S1-R2 relation is compatible.

Half of the participants started with the R1-R2 BCE task blocks, the other half with the S1-R2 BCE task blocks. Participants first performed a short practice block of 20 randomly drawn trials of the respective BCE task, followed by six experimental blocks of 64 trials, resulting from eight repetitions of all combinations of 2 S1 × 2 S2 × 2 S1 brightness. All trials were presented in a random order within each half of the experiment. Participants received written instructions that emphasized speed and accuracy, and were asked to give R1 and R2 successively in fixed order.

Design and analysis. In R1-R2 BCE blocks, trials in which the required spatial position of R1 and the required vocal R2 matched (e.g., left index finger and the utterance "links") were R1-R2 compatible, whereas the other trials were R1-R2 incompatible. In S1-R2 BCE blocks, trials in which the color of S2 and the required vocal R2 matched (e.g., a red frame and the utterance “rot”) were S1-R2 compatible, whereas the other trials were S1-R2 incompatible. Data from practice blocks and trials with task-unspecific errors (missing responses, wrong response order, two responses in one task) were excluded, as were trials with an inter-response interval (IRI) of less than 100 ms. For the analysis of RTs, trials deviating more than 2.5 standard deviations from the individual cell mean were considered as outliers and excluded from analysis. Mean correct RTs and error rates (ERs) were submitted to separate 2 × 2 × 2 Analyses of Variance (ANOVAs) with the within-subjects factors (1) compatibility (compatible vs. incompatible), (2) block type (R1-R2 BCE vs. S1-R2 BCE), and (3) S1 brightness (bright vs. dark).

Results

In the following, we focus on the Task 1 results (Task 2 results are provided in the Online Supplement[3]). Mean RT1s are visualized in Figure 3 (see also Table 1). RT1s (2.81% outliers) were 58 ms longer for incompatible (650 ms) compared to compatible trials (592 ms), $F(1,47) = 50.91$, $p < .001$, $\eta_p^2 = .52$. RT1s did not differ between R1-R2 BCE and S1-R2 BCE blocks, $F(1,47) < 0.01$, $p = .999$, $\eta_p^2 < .01$. As expected, RT1s were 23 ms longer when S1 was dark (633 ms) compared to bright (610 ms), $F(1,47) = 67.50$, $p < .001$, $\eta_p^2 = .59$. Importantly, none of the two-way interactions was significant, all Fs ≤ 0.96, all ps $\geq .333$, and the three-way interaction was also not significant, $F(1,47) = 1.99$, $p = .165$, $\eta_p^2 = .04$.

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[3] Task 2 results for Experiment 1-3 are provided in the Online Supplement, as they are irrelevant for the respective research questions.

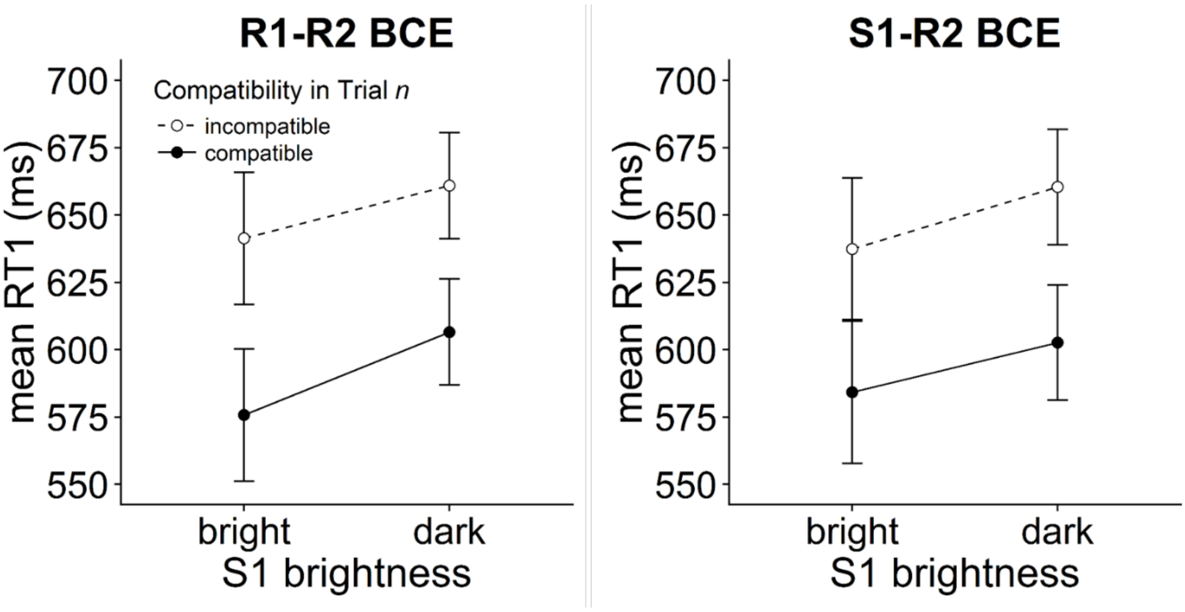

Figure 2. Mean RT2s as a function of compatibility (incompatible vs. compatible) and S1 brightness (bright vs. dark) in Experiment 1, plotted separately for R1-R2 blocks and S1-R2 blocks. Error bars are 95% within-subject confidence intervals for the respective BCE, calculated separately for bright and dark S1s (see Pfister & Janczyk, 2013).

Error rates are summarized in Table 1. Participants made more errors in incompatible (5.38%) than in compatible (2.95%) trials, $F(1,47) = 30.04$, $p < .001$, $\eta_p^2 = .39$. They also made more errors in R1-R2 BCE (4.53%) than in S1-R2 BCE (3.80%) blocks, $F(1,47) = 6.86$, $p = .012$, $\eta_p^2 = .13$. Parallelling the RT1 results, more errors occurred when S1 was dark (4.48%) relative to bright (3.86%), $F(1,47) = 6.50$, $p = .014$, $\eta_p^2 = .12$. The interaction of compatibility and blocktype was significant, $F(1,47) = 6.94$, $p = .011$, $\eta_p^2 = .13$. All other two-way interactions and the three-way interaction were not significant, all Fs ≤ 1.61, all ps $\geq .210$.

Table 1. Mean RTs (in ms) / error rates (in %) for Task 1 in Experiment 1 as a function of compatibility (incompatible vs. compatible), block type (R1-R2 BCE vs. S1-R2 BCE), and S1 brightness (bright vs. dark).

	Block type			
	R1-R2 BCE		S1-R2 BCE	
S1 brightness	Incompatible	Compatible	Incompatible	Compatible
Bright	661 / 6.77	607 / 3.16	660 / 4.46	603 / 3.51
Dark	641 / 6.16	576 / 2.03	637 / 4.14	584 / 3.09

Discussion

In Experiment 1, we tested whether the S1-R2 BCE has its locus in the perceptual stage. To this end, S1 brightness was manipulated trial-by-trial in separate blocks of R1-R2 and S1-R2 BCE tasks. Most importantly, both BCEs showed additive effects with the effect of S1 brightness.[4] This is consistent with the idea that the S1-R2 BCE does not arise at a perceptual level. Thus, the present results support the conclusion by Janczyk et al. (2018) that both the R1-R2 BCE and the S1-R2 BCE have their locus in the capacity-limited central stage of Task 1 processing.

Experiment 2

Even if one accepts that both compatibility-based BCEs have their locus in a capacity-limited stage of processing (Janczyk et al., 2018), it is still possible that the capacity-limited process underlying both BCEs differs. In particular, in the case of the S1-R2 BCE it is hard to see how automatic response activation in Task 2 could interact with a response selection process in Task 1, because the compatibility of R2 is related to S1 and not to R1. Instead, Hommel (1998) suggested that "if S2-R2 translation is automatic, this verbal code should be available long before R2 selection eventually takes place and, thus, may affect S1 processing – or at least interact with the verbal code mediating S1-R1 translation" (p. 1374). Accordingly, it is possible

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[4] We also used the R-package BayesFactor (Morey, XXX) to calculate the Bayes factors for the comparison of the interactive model against the additive model (i.e., compatibility relation + S1 brightness vs. compatibility relation + S1 brightness + compatibility relation × S1 brightness), separately for the R1-R2 BCE and the S1-R2 BCE. The resulting values were $BF_{10} = 0.11$ and $BF_{10} = 0.03$, respectively.

that another capacity-limited process of perceptual nature preceding response selection underlies the S1-R2 BCE (see Figure 3 for a first illustration). In other words, each BCE has its locus in different capacity-limited processes. Experiments 2 and 3 asked whether both types of BCEs could empirically be distinguished.

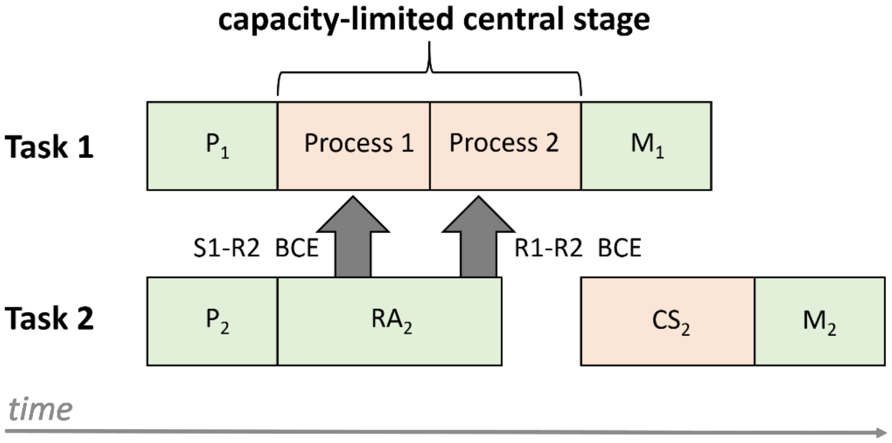

Figure 3. A preliminary model in which the capacity-limited central stage (orange) comprises two subsequent processes (Process 1 and Process 2). The first process may be of perceptual nature and underlie the S1-R2 BCE, and is followed by the process of response selection, which underlies the R1-R2 BCE. Grey arrows indicate how response activation in Task 2 feeds into these different Task 1 processes.

In these experiments, we made use of the phenomenon that the size of the BCE in a current Trial *n* does not only depend on the compatibility in the current Trial *n*, but also on the compatibility of the previous Trial *n*-1. The R1-R2 BCE is usually present following compatible trials, but absent (and sometimes even reversed) following incompatible trials (Durst & Janczyk, 2019; Janczyk, 2016; Scherbaum, Gottschalk, Dschemuchadse, & Fischer, 2015; Renas et al., 2018; see also Schuch, Dignath, Steinhauser, & Janczyk, 2019). This sequential modulation is similar to that observed in conflict tasks (see e.g., Gratton, Coles, & Donchin, 1992; Praamstra, Kleine, & Schnitzler, 1999; see also Janczyk & Leuthold, 2018; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002) and has frequently been interpreted as evidence for adaptation to a just experienced conflict (see Botvinick, Braver, Barch Carter, & Cohen, 2001; for a review, see Egner, 2007). Following the logic of Botvinick et al. (2001), in an incompatible Trial *n*-1 of a BCE task, conflict is experienced in the respective R1-R2 or S1-R2 relation, leading to subsequent adjustments visible in a smaller BCE in Trial *n*.

In Experiment 2, we manipulated both R1-R2 and S1-R2 compatibility within the same block of trials so that in each single trial a certain combination of R1-R2 and S1-R2 relation was realized. With this setup, we expected to observe sequential modulations *within* both BCEs. That is, the size of the R1-R2 BCE should depend on R1-R2 compatibility in Trial *n*-1, and the S1-R2 BCE should depend on S1-R2 compatibility in Trial *n*-1. Additionally, the present design allowed us to investigate sequential modulations *across* both BCEs. In other words, we were able to assess whether Trial *n*-1 compatibility in one of the BCEs causes a sequential modulation in the respective other BCE.

The processing loci of the two BCEs can be distinguished from the processes that lead to the sequential modulations of the BCEs. Logically, both kinds of processes can be identical or different, and thus four different scenarios are conceivable (for an illustration see Figure 4). Scenarios A and B assume identical processing loci of the two BCEs, whereas in Scenarios C and D the processing loci differ. In addition, in Scenarios A and C, the same process is responsible for the sequential modulation, whereas Scenarios B and D involve different such processes. In all of these scenarios, sequential modulations within each BCE are expected. However, the different scenarios differ in their predictions regarding the sequential modulation across the two BCEs: the Scenarios A-C imply such modulations, but Scenario D does not. Figure 5 depicts the hypothesized result pattern for Scenarios A-C with the sequential modulation across both BCEs (left panel) and Scenario D with no such modulation (right panel).

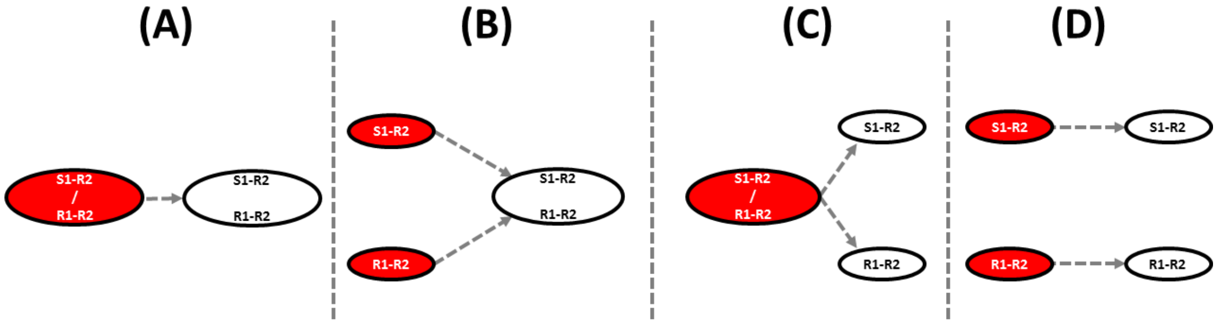

Figure 4. Illustration of the possible scenarios when the processing loci of the two BCEs (white) and the processes that lead to the sequential modulation of these effects (red) are identical or different, respectively.

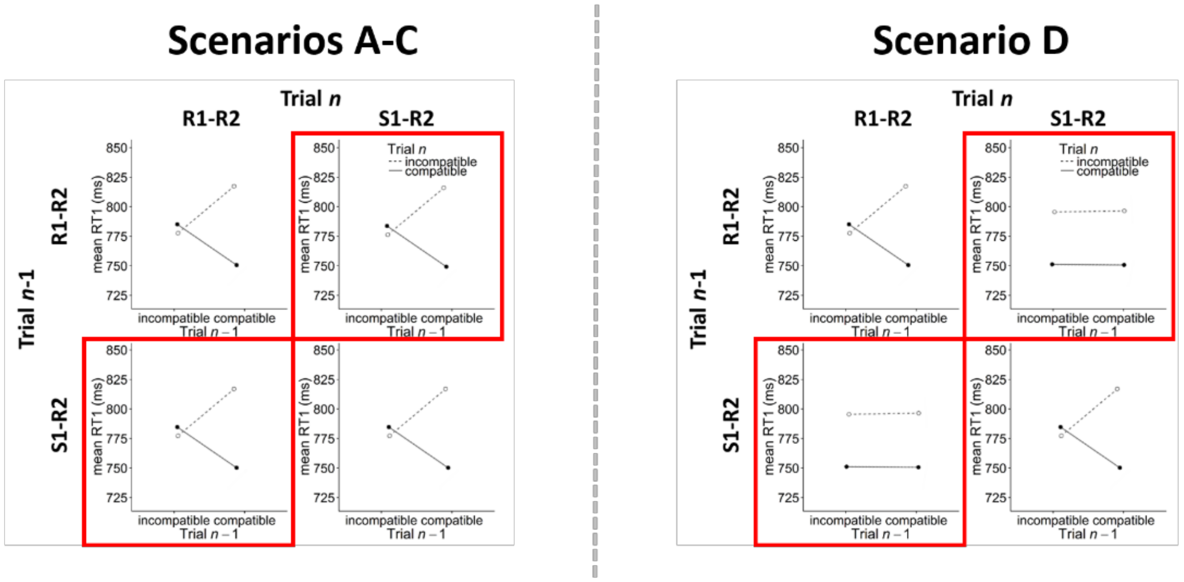

Figure 5. Illustration of the hypothesized result pattern for Scenarios A-C (left panel) and Scenario D (right panel). The crucial difference between the predictions concerns the sequential modulations *across* both BCEs (highlighted in red).

Method

Participants. Twenty-four students[5] (20 female) from the University of Tübingen, aged 18 to 36 years (M = 22.2 years, SD = 3.96), participated for monetary compensation (8€) or course credit. All participants provided written informed consent before the experiment and had normal or corrected-to-normal vision.

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[5] The critical result is the sequential modulation, that is, the two-way interaction between compatibility relations in Trial *n* and Trial *n*-1. We conducted a power analysis for this interaction assuming a large effect size (based on previous studies, e.g., Janczyk, 2016) with $\alpha = .05$ and $1 - \beta = .9$. This analysis yielded a minimum sample size of *n* = 19.

Apparatus and stimuli. Stimuli were the letters “H” or “S” colored in red or green, presented above or below the center of an otherwise black screen. R1s were given via foot pedals, one to the left and one to the right of the participant. R2s were given via manual response keys. In total, there were six manual response keys, three on each side of the participant and operated by the respective left or right index finger. The central key on each side served as the home-key, the two other keys on each side were the response keys. The response keys and the home-key were aligned in a row of three keys from the participant towards the monitor. The response keys closest to the participant will henceforth be referred to as the lower keys, whilst the response keys closest to the monitor will be referred to as the upper keys (see also Figure 6 for an illustration).

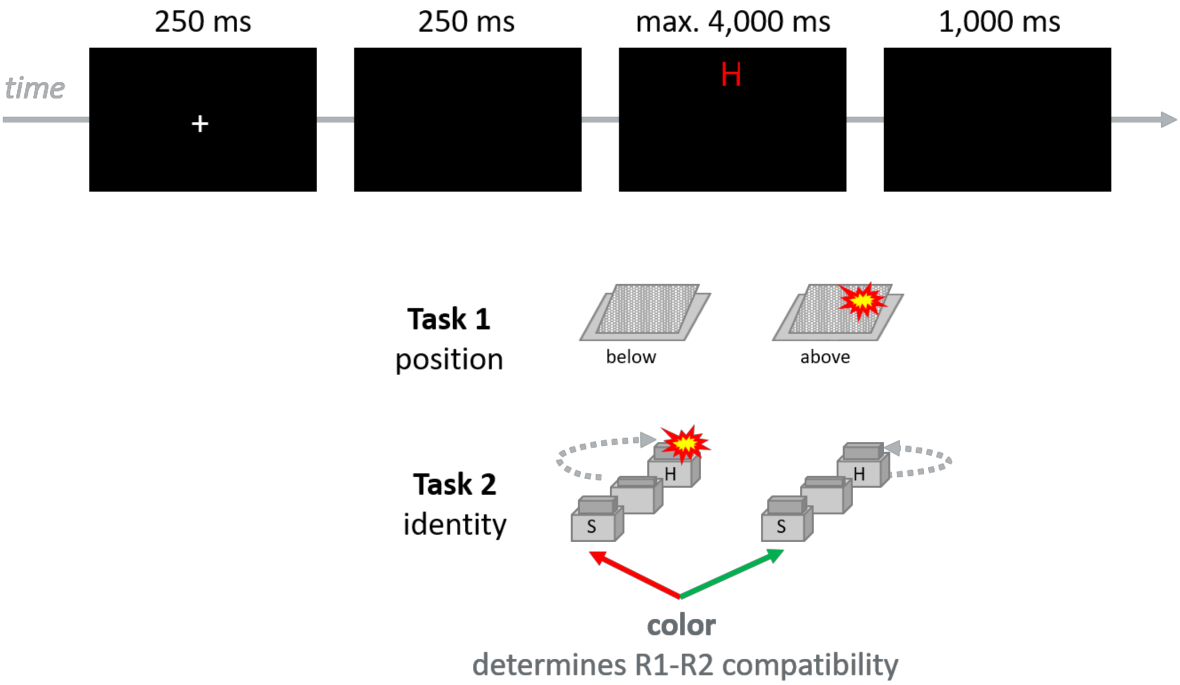

Figure 6. Trial structure and tasks in Experiment 2. In each trial, participants first responded to the position of the letter in a pedal two-choice task (Task 1). Then, participants responded to the identity of the letter in a manual two-choice task by pressing an upper or lower key (Task 2): the color cue indicated whether the respective key should be pressed on the left or right side. In the depicted example, in Task 1 a red “H” presented above the screen center requires a right pedal response. In Task 2, the identity “H” requires a response on one of the upper keys, while the color red indicates a left hand response. In this trial, the R1-R2 relation is incompatible, as both tasks require responses on different sides. However, the S1-R2 relation is compatible, as a response with an upper key matches the upper position of the letter.

Task and procedure. The trial structure and the tasks are illustrated in Figure 6. Task 1 was to respond to S1 with a pedal press of the left or right foot, and Task 2 was to respond to S2 with an index finger key-press on a lower or upper key. The color of the stimulus determined whether the key-press had to be given with the left or right index finger. The stimulus-response mapping of all tasks was counterbalanced across participants.

Participants started each trial by pressing and holding down the two home-keys. Each trial then started with a white fixation cross (250 ms), followed by a blank screen (250 ms). After that, the colored letter was presented below or above the fixation cross for a maximum of 4,000 ms or until both, R1 and R2 were registered. The next trial started after an ITI of 1,000 ms. In case of errors, specific error feedback was provided for 1,000 ms before the ITI.

Participants first performed a short practice block of 24 randomly drawn trials, which was followed by twelve experimental blocks of 48 trials each, resulting from six repetitions of all combinations of 2 S1 × 2 S2 × 2 (color cue). All trials were presented in a random order. As in Experiment 1, participants received written instructions that emphasized speed and accuracy, and were asked to give R1 and R2 successively in fixed order.

Design and analysis. Trials in which the two tasks required responses on the same side (e.g., left foot and left index finger) were R1-R2 compatible, whereas the other trials were R1-R2 incompatible. Trials in which the vertical position of the stimulus and the response key of Task 2 matched (e.g., a stimulus above the screen center and a response with an upper key) were S1-R2 compatible, whereas the other trials were S1-R2 incompatible. Data from practice and trials including task-unspecific errors (missing responses, wrong response order, two responses in one task) were excluded, as were trials with an IRI of less than 100 ms. In all analyses, trials following incorrect trials and the first trial of each block were excluded. In addition, for the analysis of RTs, the same outlier procedure as in Experiment 1 was applied. Mean correct RTs and ERs were submitted to a 2 × 2 × 2 × 2 ANOVA with the within-subjects factors (1) R1-R2 relation in Trial *n*, (2) R1-R2 relation in Trial *n*-1, (3) S1-R2 relation in Trial *n* and (4) S1-R2 relation in Trial *n*-1 (for all factors: incompatible vs. compatible).

Results

Mean RT1s are depicted in Figure 7 (see also Table 2). In the following, we will first focus on the theoretically interesting main effects, and two-way interactions reflecting sequential modulations within and across both BCEs for Task 1 (see Figure 5 for the hypothesized result patterns). The whole set of inferential statistics is reported in Table A1 of the Appendix A. A respective analysis of Task 2 performance is provided in the Online Supplement.

We excluded 2.38% of all trials as outliers. Focusing on the R1-R2 BCE, RT1s in Trial *n* were 41 ms longer for R1-R2 incompatible (813 ms) compared to R1-R2 compatible trials (772 ms), $F(1,23) = 15.84$, $p = .001$, $\eta_p^2 = .41$. RT1s were not affected by R1-R2 compatibility in Trial *n*-1, $F(1,23) = 0.22$, $p = .643$, $\eta_p^2 = .01$. The interaction of R1-R2 relation in Trial *n* and Trial *n*-1 was significant, $F(1,23) = 79.00$, $p < .001$, $\eta_p^2 = .77$, indicating a within BCE sequential modulation of the R1-R2 BCE: The R1-R2 BCE was present following compatible Trials (111 ms), $t(23) = 8.17$, $p < .001$, $d = 1.67$, and slightly inverted following incompatible Trials (-30 ms), $t(23) = -2.47$, $p = .021$, $d = -0.50$. The interaction of R1-R2 relation in Trial *n* and S1-R2 relation in Trial *n*-1 was not significant, $F(1,23) = 0.53$, $p = .474$, $\eta_p^2 = .02$, indicating that no across BCE sequential modulation occurred for the R1-R2 BCE.

Regarding the S1-R2 BCE, neither the main effect of S1-R2 relation in Trial *n*, $F(1,23) = 0.02$, $p = .902$, $\eta_p^2 < .01$, nor in Trial *n*-1 were significant, $F(1,23) = 0.03$, $p = .867$, $\eta_p^2 < .01$. Thus, unexpectedly, there was no significant S1-R2 BCE. However, there was a significant interaction between S1-R2 relation in Trial *n* and in Trial *n*-1, $F(1,23) = 15.62$, $p = .001$, $\eta_p^2 = .40$, and thus a within BCE sequential modulation of the S1-R2 BCE was present: The S1-R2 BCE was descriptively present following S1-R2 compatible trials (21 ms), $t(23) = 1.67$, $p =$

.109, *d* = 0.34, and inverted following incompatible trials (-23 ms), *t*(23) = -1.63, *p* = .117, *d* = -0.33. The interaction of S1-R2 relation in Trial *n* and R1-R2 relation in Trial *n*-1 was not significant, *F*(1,23) = 0.02, *p* = .895, η_p^2 < .01, indicating that no across BCE sequential modulation occurred.

Concerning the relationship of the two BCEs in Trial *n*, the interaction between R1-R2 and S1-R2 relation was not significant, *F*(1,23) = 0.01, *p* = .938, η_p^2 < .01. All three-way interactions were non-significant, all *F*s ≤ 0.96, all *p*s ≥ .355. Finally, the four-way interaction was significant, *F*(1,23) = 9.11, *p* = .006, η_p^2 = .28 (for further information, see Figure B1 in the Appendix B).

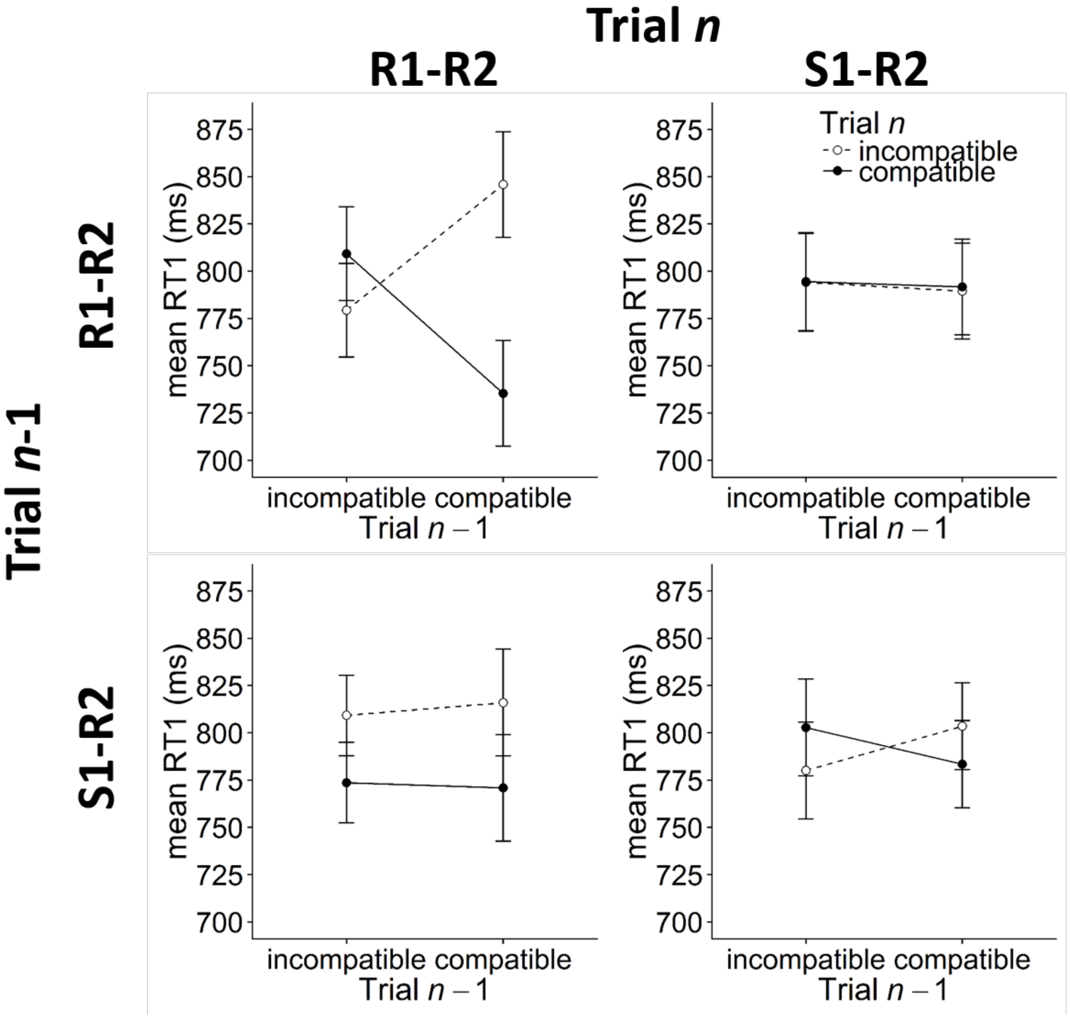

Figure 7. Mean RT1s as a function of (1) R1-R2 relation in Trial *n*, (2) R1-R2 relation in Trial *n*-1, (3) S1-R2 relation in Trial *n* and (4) S1-R2 relation in Trial *n*-1 (for each factor: incompatible vs. compatible) in Experiment

2. Error bars are 95% within-subject confidence intervals for the respective BCE in Trial *n*, calculated separately for each relationship in Trial *n*-1 (see Pfister & Janczyk, 2013).

Table 2. Mean RTs (in ms) / Error Rates (ER, in %) for Task 1 in Experiment 2 as a function of (1) R1-R2 relation in Trial *n*, (2) R1-R2 relation in Trial *n*-1, (3) S1-R2 relation in Trial *n* and (4) S1-R2 relation in Trial *n*-1. (Note: Inc = incompatible, Com = compatible)

		R1-R2			
		Trial *n*-1			
		Inc	Inc	Com	Com
S1-R2		**Trial *n***			
Trial *n*-1	**Trial *n***	Inc	Com	Inc	Com
Inc	Inc	737 / 2.00	809 / 2.23	856 / 2.08	718 / 3.30
Inc	Com	787 / 6.28	800 / 1.41	834 / 1.88	767 / 1.07
Com	Inc	822 / 2.48	809 / 2.99	857 / 4.87	750 / 1.50
Com	Com	772 / 4.10	819 / 0.54	837 / 4.14	706 / 0.92

The ER results largely mirrored the RT results (see Table 2). The ANOVA revealed that more errors occurred in R1-R2 incompatible (3.48%) relative to R1-R2 compatible (1.75%) trials, *F*(1,23) = 15.93, *p* = .001, η_p^2 = .41. The main effect of R1-R2 relation in Trial *n*-1 was not significant, *F*(1,23) = 2.40, *p* = .135, η_p^2 = .09. The interaction of R1-R2 relation in Trial *n* and in Trial *n*-1 was significant, *F*(1,23) = 37.07, *p* < .001, η_p^2 = .62, indicating a within BCE sequential modulation of the R1-R2 BCE: The R1-R2 BCE was present following compatible Trials (3.86%), *t*(23) = 6.31, *p* < .001, *d* = 1.29, and not present following incompatible Trials (-0.39%), *t*(23) = -0.70, *p* = .489, *d* = -0.14. The interaction of R1-R2 relation in Trial *n* and S1-R2 relation in Trial *n*-1 was not significant, *F*(1,23) = 0.06, *p* = .810, η_p^2 < .01, and thus no across BCE sequential modulation occurred for the R1-R2 BCE.

Neither the main effect of S1-R2 relation in Trial *n*, *F*(1,23) = 0.76, *p* = .394, η_p^2 = .03, nor in Trial *n*-1 was significant, *F*(1,23) = 2.60, *p* = .120, η_p^2 = .10. Further, the interaction of

S1-R2 relation in Trial *n* and in Trial *n*-1 was not significant, $F(1,23) = 0.16$, $p = .691$, $\eta_{\mathrm{p}}^2 = .01$, as was the interaction of S1-R2 relation in Trial *n* and R1-R2 relation in Trial *n*-1, $F(1,23) = 0.04$, $p = .848$, $\eta_{\mathrm{p}}^2 < .01$. Thus, neither a within BCE sequential modulation, nor an across BCE sequential modulation was present for the S1-R2 BCE in error rates.

As for RT1s, the interaction between R1-R2 relation in Trial *n* and S1-R2 relation in Trial *n* was not significant, $F(1,23) = 0.44$, $p = .513$, $\eta_{\mathrm{p}}^2 = .02$. There was a significant interaction between S1-R2 relation in Trial *n*, S1-R2 relation in Trial *n*-1, and R1-R2 relation in Trial *n*-1, $F(1,23) = 4.97$, $p = .036$, $\eta_{\mathrm{p}}^2 = .18$. All other three-way interactions, *F*s ≤ 2.15, all *p*s $\geq .156$, and the four-way interaction were not significant, $F(1,23) = 0.21$, $p = .654$, $\eta_{\mathrm{p}}^2 = .01$.

Discussion

Experiment 2 demonstrates sequential modulations within the S1-R2 as well as the R1-R2 BCE (Janczyk, 2016). Further and in line with the assumptions of Scenario D (see Figure 4), no across BCE sequential modulations were obtained. In other words: The R1-R2 BCE in Trial *n* was modulated only by the R1-R2 relation, but not by the S1-R2 relation, in Trial *n*-1. The same pattern was observed for the S1-R2 BCE in Trial *n*. That is, the S1-R2 BCE in Trial *n* was modulated only by the S1-R2 relation, but not by the R1-R2 relation, in Trial *n*-1. In addition, none of the three-way interactions was significant, providing further evidence that the sequential modulations as indicated by the two-way interactions were not further modulated. One unexpected result was the lack of a S1-R2 BCE in Trial *n*, which may have been overshadowed by its sequential modulation. Another aspect of the present design which might have contributed to this result was that the special role of the color cue with respect to the R1-R2 relation might have reduced the salience of the S1-R2 compared to the R1-R2 relation. Despite this, the present results can be taken as first evidence that the two BCEs can be distinguished empirically and perhaps are based on different capacity-limited processes.

Experiment 3

The results of Experiment 2 fit well with the idea that the two BCEs emerge from different underlying processes. To corroborate and generalize these results, we replicated Experiment 2 with a larger sample size and a minor change of the design. Specifically, we changed the role of the color cue so that it now determined S1-R2 instead of R1-R2 compatibility. With this change, we attempted to invert the possible asymmetry regarding the salience of the S1-R2 and R1-R2 relation in Experiment 2.

Method

Participants. Fourty-eight students (33 female) from the University of Tübingen, aged 18 to 29 years (M = 22.8 years, SD = 3.84), participated for monetary compensation (8€) or course credit. All participants provided written informed consent before the experiment and had normal or corrected-to-normal vision.

Apparatus and stimuli. The apparatus and stimuli were the same as in Experiment 2.

Task and procedure. The trial structure and tasks are illustrated in Figure 8. Task 1 was to respond to S1 with a pedal press of the left or right foot, and Task 2 was to respond to S2 with an index finger key-press of a left or right key. The color of the stimulus determined whether the index finger key-press had to be given on a lower or upper key. Otherwise, the procedure was the same as in Experiment 2.

Design and analysis. Design and data analysis were the same as in Experiment 2.

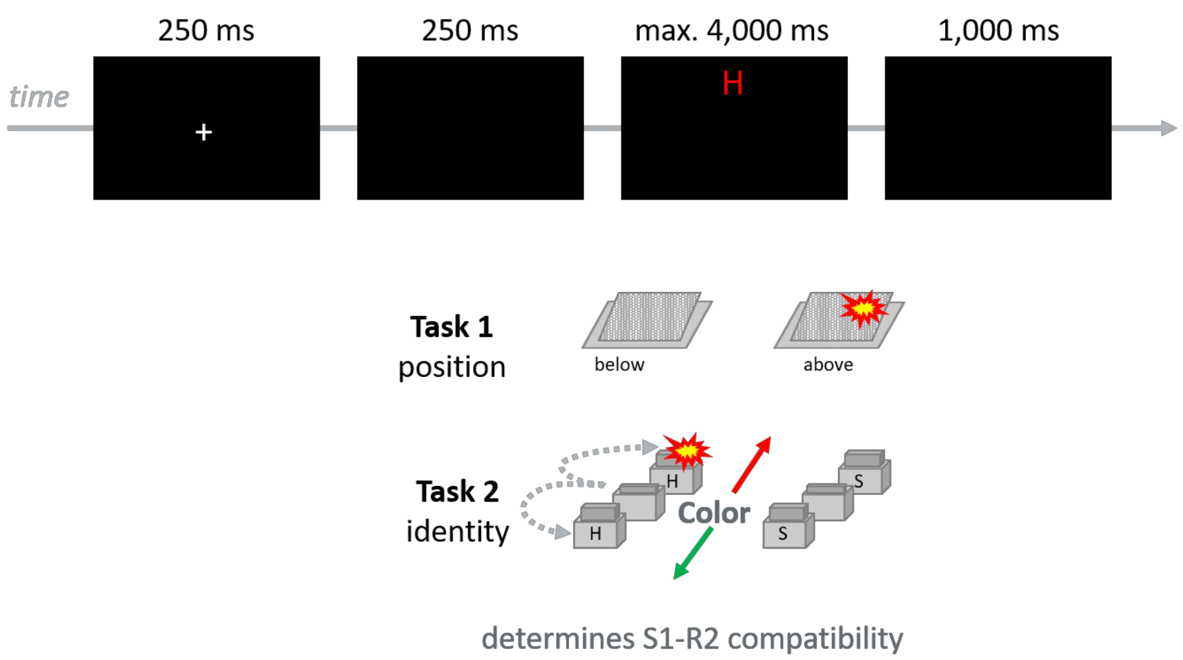

Figure 8. Trial structure and tasks in Experiment 3. In each trial, participants first responded to the position of the letter in a pedal two-choice task (Task 1). Then, participants responded to the identity of the letter in a manual two-choice task by pressing a left or right key (Task 2): The color cue indicated whether the respective upper or lower key should be pressed. In the depicted example, in Task 1 a red "H" presented above the screen center requires a right pedal response. In Task 2, the identity "H" requires a response with one of the left keys and the color red indicates a response on the respective upper key. In this trial example, the R1-R2 relation is incompatible, as both responses are required on different sides. However, the S1-R2 relation is compatible, as a response with an upper key matches the upper position of the letter. Note that the role of the color cue changed from Experiment 2.

Results

Mean RT1s are depicted in Figure 8 (see also Table 6 for mean RTs and ERs in Task 1). As for Experiment 2, the whole set of inferential statistics is summarized in Table A1 of the Appendix A, and a respective analysis of Task 2 performance is provided in the Online Supplement.

We excluded 2.34% of all trials as outliers. Regarding the R1-R2 BCE, RT1s were 24 ms longer for R1-R2 incompatible (885 ms) than for R1-R2 compatible trials (861 ms), $F(1,47) = 15.50$, $p < .001$, $\eta_p^2 = .25$. RT1s were not affected by R1-R2 relation in Trial *n*-1, $F(1,47) = 1.06$, $p = .309$, $\eta_p^2 = .02$. The interaction of R1-R2 relation in Trial *n* and in Trial *n*-1 was significant, $F(1,47) = 38.91$, $p < .001$, $\eta_p^2 = .45$, indicating a within BCE sequential modulation of the R1-R2 BCE: The R1-R2 BCE was present following compatible trials (72 ms), $t(47) = 7.72$, $p < .001$, $d = 1.11$, and inverted following incompatible trials (-24 ms), $t(47) = -2.33$, $p = .024$, $d = -0.34$. The interaction of R1-R2 relation with S1-R2 relation in Trial *n*-1 was not significant, $F(1,47) = 0.74$, $p = .395$, $\eta_p^2 = .02$, indicating that no across BCE sequential modulation occurred for the R1-R2 BCE.

Concerning the S1-R2 BCE, neither the main effect of S1-R2 relation in Trial *n*, $F(1,47) = 0.16$, $p = .693$, $\eta_p^2 < .01$, nor in Trial *n*-1 was significant, $F(1,47) = 0.21$, $p = .651$, $\eta_p^2 < .01$. The interaction of S1-R2 relation in Trial *n* and in Trial *n*-1 was significant, $F(1,47) = 58.14$, $p < .001$, $\eta_p^2 = .55$, indicating a within BCE sequential modulation of the S1-R2 BCE: There was a significant S1-R2 BCE following compatible trials (53 ms), $t(47) = 4.32$, $p < .001$, $d = 0.62$, and an inverted one following incompatible trials (-61 ms), $t(47) = -4.61$, $p < .001$, $d = -0.66$. The interaction of S1-R2 relation in Trial *n* and R1-R2 relation in Trial *n*-1 was not significant, $F(1,47) = 2.36$, $p = .131$, $\eta_p^2 = .05$, indicating that no across BCE sequential modulation for the S1-R2 BCE was present.

Regarding the relationship of the two BCEs in Trial *n*, the interaction was not significant, $F(1,47) = 0.02$, $p = .891$, $\eta_p^2 < .01$. All three-way interactions were not significant, all Fs ≤ 1.89, all ps $\geq .175$. However, the four-way interaction was significant, $F(1,47) = 11.70$, $p = .001$, $\eta_p^2 = .20$ (for more information, see Figure B1 in the Appendix B).

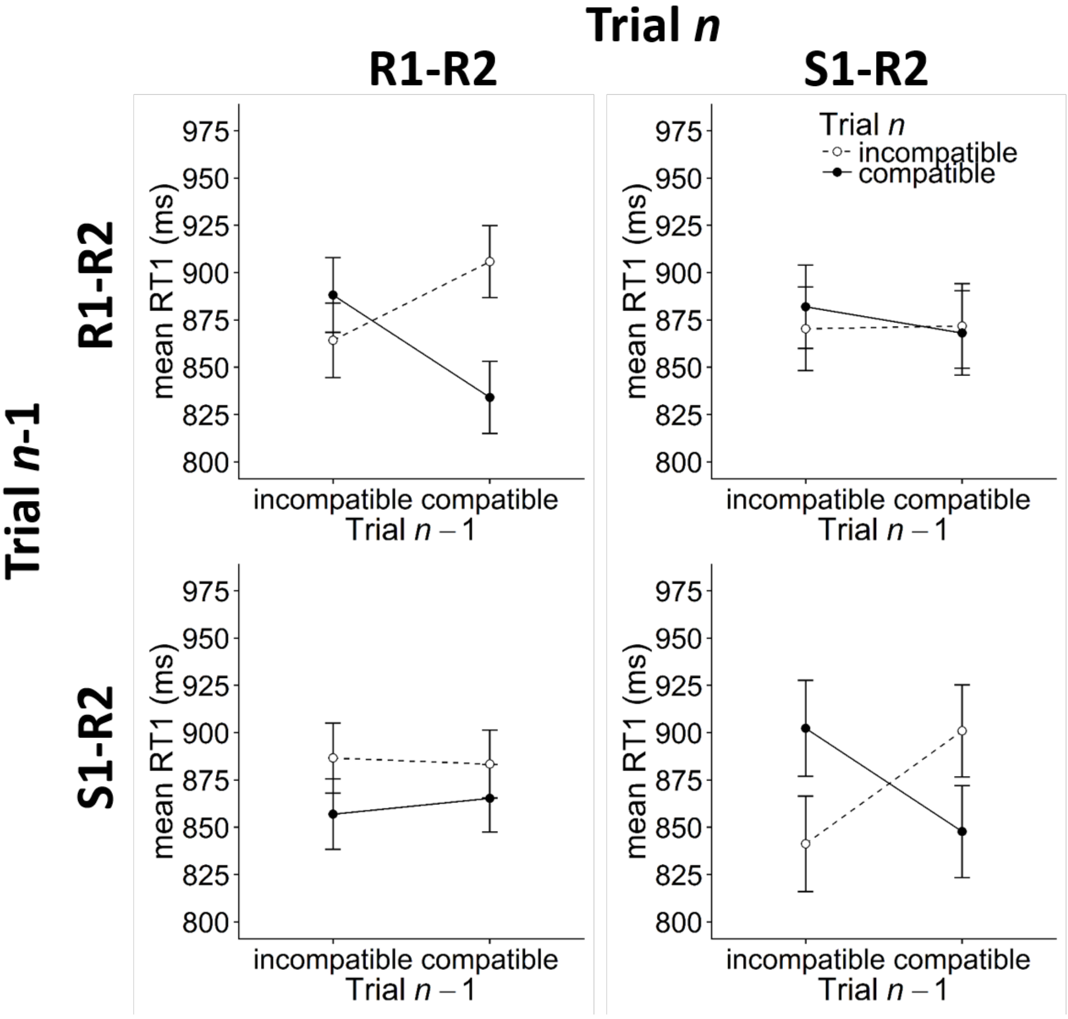

Figure 9. Mean RT1s as a function of (1) R1-R2 relation in Trial *n*, (2) R1-R2 relation in Trial *n*-1, (3) S1-R2 relation in Trial *n* and (4) S1-R2 relation in Trial *n*-1 (for each factor: incompatible vs. compatible) in Experiment 3. Error bars are 95% within-subject confidence intervals for the respective BCE in Trial *n*, calculated separately for each relationship in Trial *n*-1 (see Pfister & Janczyk, 2013).

The ER results again mirrored the RT results. The ANOVA revealed that more errors were made in R1-R2 incompatible (0.03%) than in R1-R2 compatible (0.02%) trials, $F(1,47) = 10.88$, $p = .002$, $\eta_p^2 = .19$. More errors also occurred following R1-R2 compatible (3.06%) compared to incompatible trials (2.48%), $F(1,47) = 7.99$, $p = .007$, $\eta_p^2 = .15$. The interaction of R1-R2 relation in Trial *n* and Trial *n*-1 was significant, $F(1,47) = 24.11$, $p < .001$, $\eta_p^2 = .34$, indicating a within BCE sequential modulation of the R1-R2 BCE: The R1-R2 BCE was significant following compatible trials (0.02%), $t(47) = 4.63$, $p < .001$, $d = 0.67$, but not following incompatible trials (0.00%), $t(47) = -0.55$, $p = .586$, $d = -0.08$. The interaction of R1-

R2 relation in Trial *n* and S1-R2 relation in Trial *n*-1 was not significant, $F(1,47) = 1.45$, $p = .235$, $\eta^2_p = .03$.

There was no main effect of S1-R2 relation in Trial *n*, $F(1,47) = 0.30$, $p = .586$, $\eta^2_p = .01$, nor in Trial *n*-1, $F(1,47) = 0.30$, $p = .584$, $\eta^2_p = .01$. The interaction of S1-R2 relation in Trial *n* and in Trial *n*-1 was significant, $F(1,47) = 22.14$, $p < .001$, $\eta^2_p = .32$, indicating a within BCE sequential modulation of the S1-R2 BCE: The S1-R2 BCE was significant following compatible trials (1.2%), $t(47) = 3.24$, $p = .002$, $d = 0.47$, and inversed following incompatible trials (-0.91%), $t(47) = -2.75$, $p = .008$, $d = -0.40$. The interaction of S1-R2 relation in Trial *n* and R1-R2 relation in Trial *n*-1 was not significant, $F(1,47) = 0.02$, $p = .882$, $\eta^2_p < .01$, indicating that no across BCE sequential modulation occurred for the S1-R2 BCE.

The interaction between R1-R2 relation in Trial *n* and S1-R2 relation in Trial *n* was not significant, $F(1,47) = 0.15$, $p = .703$, $\eta^2_p < .01$. There was a significant interaction between S1-R2 relation in Trial *n,* S1-R2 relation in Trial *n*-1, and R1-R2 relation in Trial *n*-1, $F(1,47) = 4.95$, $p = .031$, $\eta^2_p = .10$. All other three-way interactions, all *F*s ≤ 1.49, all *p*s ≥ .228, and the four-way interaction were not significant, $F(1,47) = 0.27$, $p = .608$, $\eta^2_p = .01$.

Table 3. Mean RTs (in ms) / and Error Rates (ER, in %) for Task 1 in Experiment 3 as a function of (1) R1-R2 relation in Trial *n*, (2) R1-R2 relation in Trial *n*-1, (3) S1-R2 relation in Trial *n* and (4) S1-R2 relation in Trial *n*-1. (Note: Inc = incompatible, Com = compatible)

		R1-R2			
		Trial *n*-1			
		Inc	Inc	Com	Com
S1-R2		**Trial *n***			
Trial *n*-1	**Trial *n***	Inc	Com	Inc	Com
Inc	Inc	804 / 1.94	871 / 2.98	899 / 2.72	791 / 3.10
Inc	Com	920 / 3.51	902 / 1.08	923 / 4.90	864 / 2.44
Com	Inc	902 / 2.72	904 / 2.48	925 / 2.04	873 / 1.82
Com	Com	830 / 5.36	875 / 2.65	876 / 3.61	809 / 0.93

Discussion

The results of Experiment 3 were remarkably similar to those of Experiment 2. Again and consistent with Scenario D of Figure 4, across BCE sequential modulations were observed. Also, there was again a sequential within S1-R2 modulation, even though no significant S1-R2 BCE in Trial *n* occurred. Thus, our attempt to change a possible asymmetry in the salience of the two BCEs proved insufficient. Nevertheless, Experiment 3 provides further evidence for different processing loci of the two BCEs.

General Discussion

The present study set out to investigate the processing loci of the S1-R2 and the R1-R2 compatibility-based BCEs. Experiment 1 built on a result reported by Janczyk et al. (2018, Exp. 3) and tested whether the locus of the S1-R2 BCE is perceptual or not. S1 brightness, which was manipulated trial-by-trial in separate blocks of R1-R2 BCE and S1-R2 BCE tasks, interacted neither with R1-R2 nor with S1-R2 compatibility. This result is inconsistent with a perceptual locus of the S1-R2 BCE (see Sternberg, 1969). Together with the results of Janczyk et al., both BCEs thus seem to have their loci in the capacity-limited central stage.

However, although both BCEs likely reflect capacity-limited processing, it remains possible that different processes underlie the two effects. Experiment 2 and 3 thus investigated whether the processing loci of the two BCEs can be further distinguished. To this end, we investigated possible across BCE sequential modulations in a setup where both S1-R2 and R1-R2 compatibility varied within the same block of trials. The crucial question was whether the compatibility relation in one type of BCE would cause sequential modulations of the other type. Such across BCE sequential modulations would suggest similar underlying processes for both types of BCEs and/or their sequential modulations (Scenarios A-C in Figure 4). An absence of such modulations, however, would suggest different underlying processes for the two BCEs

(Scenario D in Figure 4). Results of Experiment 2 and 3 are in line with the latter prediction: In both experiments, we obtained sequential modulations within but not across the two BCEs. Thus, the present results indicate that the two BCEs should be conceived of as two different types of compatibility-based BCEs.

How are the compatibility-based BCEs different? The present results can be accounted for by a model assuming that two different processes occur in the capacity-limited central stage, each responsible for the emergence of one type of compatibility-based BCE (see Figure 3). Previous studies have attributed the R1-R2 BCE to interference between Task 1 response selection and simultaneous Task 2 response activation. This appears reasonable, because there is a spatial overlap between the two responses and therefore Task 2 response activation can facilitate Task 1 response selection in compatible trials and counteract it in incompatible trials (see Durst & Janczyk, 2019, for a more detailed account). For the S1-R2 BCE, however, the dimensional overlap is not between the two responses, but between the stimulus in Task 1 and the response in Task 2.

How, then, can the underlying processes of the S1-R2 BCE be specified? Consider an experiment in which the color of a letter requires a manual response with the left or right index finger as Task 1. In Task 2, the identity of the letter requires a vocal utterance of the words “green” or “red” (Task 2; see also, Hommel, 1998, Experiment 2), conceivably leading to an activation of the associated color feature (e.g., the stimulus “H” is associated with the color “green”). This activation may affect ongoing Task 1 processes. However, it is unlikely that this activation influences response selection, as there is neither spatial nor semantic overlap with the spatially defined response in Task 1. It appears more plausible that the color activation affects an earlier capacity-limited Task 1 process that still deals with S1 (see also Hommel, 1998, p. 1374).

A plausible candidate for such a process is stimulus categorization, which has been shown to be a capacity-limited process (Johnston & McCann, 2006). Furthermore, semantic category-response rules instead of stimulus-response rules appear to be held in working memory for both the S1-R2 BCE (Ellenbogen & Meiran, 2008) and the R1-R2 BCE (Thomson, Watter, & Finkelshtein, 2010), and semantic memory retrieval in Task 2 can run in parallel with Task 1 central stage (Fischer, Miller, & Schubert 2007; Oriet, Tombu, & Jolicoeur, 2005). For our example, this means that the automatic Task 2 activation of "green" adds to the activation resulting from categorizing the relevant Task 1 stimulus as green or red. Then, in compatible trials, a sufficient amount of activation for decisive categorization is reached earlier, whereas in incompatible trials it is reached later (see Figure 9, for an illustration).

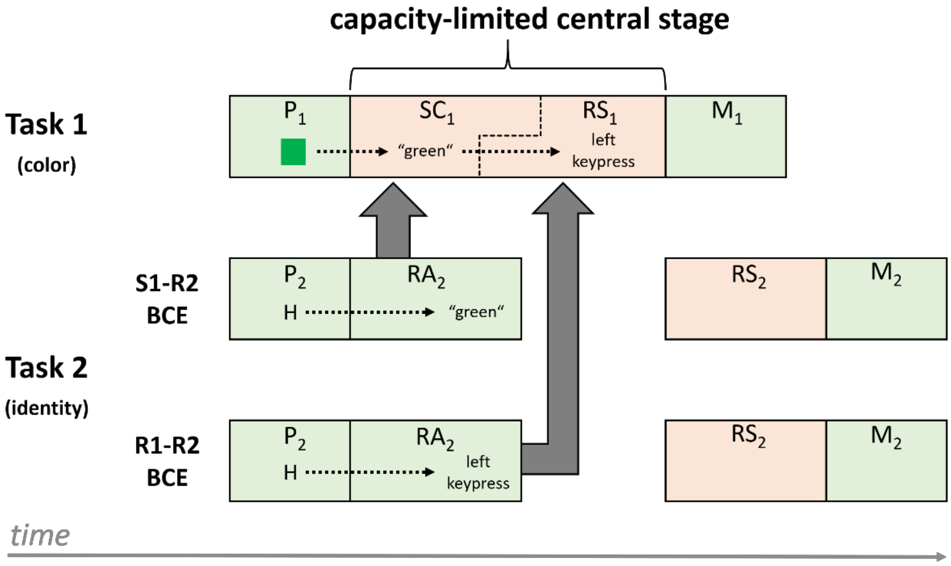

Figure 10. Illustration of a model in which the capacity-limited central stage (orange) comprises two processes separated by a dashed line. Task 2 (the identity task) is illustrated separately for the S1-R2 BCE and the R1-R2 BCE. Note that the stimuli and responses shown here are taken from Experiment 1 (R1-R2 BCE) and 2 (S1-R2 BCE) by Hommel (1998). The model assumes that the locus of the S1-R2 BCE is in the first capacity-limited process of stimulus categorization (SC), whereas the locus of the R1-R2 BCE is in the second capacity-limited process of response selection (RS). Grey arrows indicate the source of the two BCEs in response activation (RA) of Task 2. (P = perceptual stage, M = motor stage, the subscript indicates Task 1 and 2, respectively)

The present results indicate that the two BCEs have their loci in different capacity-limited processes, that is, stimulus categorization and response selection, respectively. A further question is whether these processes run (partially) in parallel or whether they proceed in a strictly serial manner within Task 1. The present data do not support the former notion. We suggest that stimulus categorization gets a head start over response selection, because the latter necessarily requires at least some output from stimulus categorization to initiate application of the category-response rule. As soon as stimulus categorization is fully finished, response selection can run at full efficiency. Similar category-response translations seem to be involved also in a category-match effect, that is, shorter RT1s when S1 and S2 belong to the same rather than different semantic categories (e.g., when both stimuli are digits compared to when S1 is a letter and S2 is a digit; e.g., Logan & Schulkind, 2000; Thomson et al., 2010). Whether and to what extent the category-match effect is similar to the R1-R2 and the S1-R2 BCE remains an open question.

Caveats and limitations. An unexpected observation of the present study was the absence of an S1-R2 BCE in Experiments 2 and 3, whereas a clear S1-R2 BCE was observed in Experiment 1. One obvious difference between these experiments is the type of S1-R2 relation: In Experiment 1, the relation was conceptual (i.e., the color of S1 and the utterance of a color word as R2; e.g., Hommel, 1998), whereas in the other experiments, the relation was spatial (i.e., the vertical position of S1 and R2; see also Lien et al., 2007). This change in the design was necessary in order to investigate potential sequential modulations across the two BCEs in Experiments 2 and 3 (see also below). Second, we hypothesized that the special role of the color cue in the present design might have contributed to this result. However, changing the role of the color cue in Experiment 3 did not affect the result pattern. Third, the S1-R2 relation in Experiments 2 and 3 was based on the vertical position of the stimulus and the required response, as participants were instructed to press an upper or lower key. One might argue that the arrangement of the response keys was not vertically aligned but rather according to the sagittal axis of the body (i.e., near and far response keys). While this might have reduced the dimensional overlap between S1 and R2, instances of orthogonal spatial compatibility effects have also been reported (e.g., Koch & Jolicœur, 2007; Nishimura & Yokosawa, 2006). Importantly, we believe that the absence of an S1-R2 BCE in Trial *n* does not undermine our conclusions, because a clear within S1-R2 BCE sequential modulation was observed in Experiments 2 and 3.

It should also be noted that the design of Experiments 2 and 3 was slightly unusual in that both BCE were investigated within the same blocks of trials. Alternatively, it would have been possible to present the two BCEs in alternating runs (see Rogers & Monsell, 1995), in which two trials of one BCE are followed by two trials of the other BCE. We decided not to employ such a procedure for several reasons. First, this would have required participants to switch between different tasks rules for Task 2 every second trial. Second, we reasoned that a stronger separation of the two tasks could have possibly counteracted sequential modulations (for a discussion of the potential influence of task characteristics on sequential modulations, see Braem, Abrahamse, Duthoo, & Notebaert, 2014).

Conclusion. The present results indicate that even though both compatibility-based BCEs have their locus in the capacity-limited stage, they are nonetheless based on different processes. As a working hypothesis, we suggest that response activation in Task 2 affects response selection in Task 1 in case of the R1-R2 BCE, but stimulus categorization in case of the S1-R2 BCE.

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References

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review, 108,* 624–652.

Braem, S., Abrahamse, E. L., Duthoo, W., & Notebaert, W. (2014). What determines the specificity of conflict adaptation? A review, critical analysis, and proposed synthesis. *Frontiers in psychology, 5*, 1134.

Durst, M., & Janczyk, M. (2018). The motor locus of no-go backward crosstalk. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 44,* 1931-1946.

Durst, M., & Janczyk, M. (2019). Two types of backward crosstalk: Sequential modulations and evidence from the diffusion model. *Acta Psychologica, 193, 132-152.* doi:https://doi.org/10.1016/j.actpsy.2018.11.013

Egner, T. (2007). Congruency sequence effects and cognitive control. *Cognitive, Affective & Behavioral Neuroscience, 7,* 380–390.

Ellenbogen, R., & Meiran, N. (2008). Working memory involvement in dual-task performance: Evidence from the backward compatibility effect. *Memory & Cognition, 36,* 968-978.

Fischer, R., Miller, J., & Schubert, T. (2007). Evidence for parallel semantic memory retrieval in dual tasks. *Memory & Cognition, 35,* 1685-1699.

Gratton, G., Coles, M. G., & Donchin, E. (1992). Optimizing the use of information: Strategic control of activation of responses. *Journal of Experimental Psychology: General, 121,* 480–506.

Hommel, B. (1998). Automatic stimulus–response translation in dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 1368-1384.

Hommel, B., & Eglau, B. (2002). Control of stimulus-response translation in dual-task performance. *Psychological Research, 66,* 260-273.

Janczyk, M. (2016). Sequential modulation of backward crosstalk and task-shielding in dual-tasking. *Journal of Experimental Psychology: Human Perception and Performance, 42,* 631-647.

Janczyk, M., & Leuthold, H. (2018). Effector system-specific sequential modulations of congruency effects. *Psychonomic Bulletin & Review, 25,* 1066-1072.

Janczyk, M., Pfister, R., Hommel, B., & Kunde, W. (2014). Who is talking in backward crosstalk? Disentangling response-from goal-conflict in dual-task performance. *Cognition, 132,* 30-43.

Janczyk, M., Pfister, R., Wallmeier, G., & Kunde, W. (2014). Exceptions to the PRP effect? A comparison of prepared and unconditioned reflexes. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*, 776.

Janczyk, M., Renas, S., & Durst, M. (2018). Identifying the locus of compatibility-based backward crosstalk: Evidence from an extended PRP paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 44,* 261-276.

Johnston, J. C., & McCann, R. S. (2006). On the locus of dual-task interference: Is there a bottleneck at the stimulus classification stage? *The Quarterly Journal of Experimental Psychology, 59,* 694-719.

Koch, I. & Jolicoeur, P. (2007). Orthogonal cross-task compatibility: Abstract spatial coding in dual tasks. *Psychonomic Bulletin & Review, 14,* 45-50.

Lien, M.-C., & Proctor, R. W. (2000). Multiple spatial correspondence effects on dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 1260-1280.

Lien, M.-C., & Proctor, R. W. (2002). Stimulus-response compatibility and psychological refractory period effects: Implications for response selection. *Psychonomic Bulletin & Review, 9,* 212-238.

Lien, M.-C., Ruthruff, E., Hsieh, S., & Yu, Y.-T. (2007). Parallel central processing between tasks: Evidence from lateralized readiness potentials. *Psychonomic Bulletin & Review, 14,* 133-141.

Logan, G. D., & Schulkind, M. D. (2000). Parallel memory retrieval in dual-task situations: I. Semantic memory. *Journal of Experimental Psychology: Human Perception and Performance, 26,* 1072-1090.

Miller, J., & Durst, M. (2014). “Just do it when you get a chance”: The effects of a background task on primary task performance. *Attention, Perception, & Psychophysics, 76,* 2560-2574.

Miller, J., & Durst, M. (2015). A comparison of the psychological refractory period and prioritized processing paradigms: Can the response-selection bottleneck model explain them both? *Journal of Experimental Psychology: Human Perception and Performance, 41,* 1420-1441.

Morey, R. D., & Rouder, J. N. (2015). *BayesFactor 0.9.11-1.* Comprehensive R Archive Network.

Nishimura, A., & Yokosawa, K. (2006). Orthogonal stimulus–response compatibility effects emerge even when the stimulus position is task irrelevant. *The Quarterly Journal of Experimental Psychology*, *59*(6), 1021-1032.

Oriet, C., Tombu, M., & Jolicoeur, P. (2005). Symbolic distance affects two processing loci in the number comparison task. *Memory & Cognition, 33,* 913-926.

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin, 116,* 220-244.

Pashler, H., & Johnston, J. C. (1989). Chronometric evidence for central postponement in temporally overlapping tasks. *The Quarterly Journal of Experimental Psychology, 41,* 19-45.

Pfister, R., & Janczyk, M. (2013). Confidence intervals for two sample means: Calculation, interpretation, and a few simple rules. *Advances in Cognitive Psychology, 9,* 74-80.

Praamstra, P., Kleine, B. U., & Schnitzler, A. (1999). Magnetic stimulation of the dorsal premotor cortex modulates the Simon effect. *Neuroreport, 10,* 3671–3674.

Renas, S., Durst, M., & Janczyk, M. (2018). Action effect features, but not anatomical features, determine the backward crosstalk effect: Evidence from crossed-hands experiments. *Psychological Research, 82,* 970-980.

Rogers, R. D., & Monsell, S. (1995). Costs of a predictible switch between simple cognitive tasks. *Journal of Experimental Psychology: General, 124*, 207-231.

Scherbaum, S., Gottschalk, C., Dshemuchadse, M., & Fischer, R. (2015). Action dynamics in multitasking: The impact of additional task factors on the execution of the prioritized motor movement. *Frontiers in Psychology, 6,* 934.

Schuch, S., Dignath, D., Steinhauser, M., & Janczyk, M. (2019). Monitoring and control in multitasking. *Psychonomic Bulletin & Review, 26,* 222-240.

Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. *Acta Psychologica, 30,* 276-315.

Stürmer, B., Leuthold, H., Soetens, E., Schröter, H., & Sommer, W. (2002). Control over location-based response activation in the Simon task: Behavioral and electrophysiological evidence. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 1345–1363.

Thomson, S. J., Danis, L. K., & Watter, S. (2015). PRP training shows Task1 response selection is the locus of the backward response compatibility effect. *Psychonomic Bulletin & Review, 22,* 212-218.

Thomson, S. J., Watter, S., & Finkelshtein, A. (2010). Parallel response selection in dual-task situations via automatic category-to-response translation. *Attention, Perception, & Psychophysics, 72,* 1791-1802.

Watter, S., & Logan, G. D. (2006). Parallel response selection in dual-task situations. *Perception & Psychophysics, 68,* 254-277.

Welford, A. T. (1952). The ‘psychological refractory period’ and the timing of high-speed performance—a review and a theory. *British Journal of Psychology. General Section, 43,* 2-19.

Appendix A: Inferential statistics for Task 1 in Experimens 2 and 3.

Table A1. ANOVA results for Task 1 RTs in Experiment 2 and 3.

Effect	**Experiment 2 (see Fig. 7)**	**Experiment 3 (see Fig. 9)**
R1-R2 Trial *n*	$F(1,23) = 15.84$, $p = .001$, $\eta_p^2 = .41$	$F(1,47) = 15.50$, $p < .001$, $\eta_p^2 = .25$
R1-R2 Trial *n*-1	$F(1,23) = 0.22$, $p = .643$, $\eta_p^2 = .01$	$F(1,47) = 1.06$, $p = .309$, $\eta_p^2 = .02$
R1-R2 Trial *n* × R1-R2 Trial *n*-1	$F(1,23) = 79.00$, p $< .001$, $\eta_p^2 = .77$	$F(1,47) = 38.91$, $p < .001$, $\eta_p^2 = .45$
R1-R2 Trial n × S1-R2 Trial *n*-1	$F(1,23) = 0.53$, $p = .474$, $\eta_p^2 = .02$	$F(1,47) = 0.74$, $p = .395$, $\eta_p^2 = .02$
S1-R2 Trial *n*	$F(1,23) = 0.02$, $p = .902$, $\eta_p^2 < .01$	$F(1,47) = 0.16$, $p = .693$, $\eta_p^2 < .01$
S1-R2 Trial *n*-1	$F(1,23) = 0.03$, $p = .867$, $\eta_p^2 < .01$	$F(1,47) = 0.21$, $p = .651$, $\eta_p^2 < .01$
S1-R2 Trial *n* × S1-R2 Trial *n*-1	$F(1,23) = 15.62$, $p = .001$, $\eta_p^2 = .40$	$F(1,47) = 58.14$, $p < .001$, $\eta_p^2 = .55$
S1-R2 Trial *n* × R1-R2 Trial *n*-1	$F(1,23) = 0.02$, $p = .895$, $\eta_p^2 < .01$	$F(1,47) = 2.36$, $p = .131$, $\eta_p^2 = .05$
R1-R2 Trial *n* × S1-R2 Trial *n*	$F(1,23) = 0.01$, $p = .938$, $\eta_p^2 < .01$	$F(1,47) = 0.02$, $p = .891$, $\eta_p^2 < .01$
R1-R2 Trial *n*-1 × S1-R2 Trial *n*-1	$F(1,23) = 6.54$, $p = .018$, $\eta_p^2 = .22$	$F(1,47) = 0.02$, $p = .881$, $\eta_p^2 < .01$
R1-R2 Trial *n* × S1-R2 Trial *n* × R1-R2 Trial *n*-1	$F(1,23) = 0.00$, $p = .979$, $\eta_p^2 < .01$	$F(1,47) = 1.81$, $p = .184$, $\eta_p^2 = .04$
R1-R2 Trial *n* × S1-R2 Trial *n* × S1-R2 Trial *n*-1	$F(1,23) = 0.24$, $p = .629$, $\eta_p^2 = .01$	$F(1,47) = 1.89$, $p = .175$, $\eta_p^2 = .04$
R1-R2 Trial *n* × R1-R2 Trial *n*-1 × S1-R2 Trial *n*-1	$F(1,23) = 0.89$, $p = .355$, $\eta_p^2 = .04$	$F(1,47) = 1.43$, $p = .238$, $\eta_p^2 = .03$
S1-R2 Trial *n* × R1-R2 Trial *n*-1 × S1-R2 Trial *n*-1	$F(1,23) = 0.02$, $p = .898$, $\eta_p^2 < .01$	$F(1,47) = 0.71$, $p = .405$, $\eta_p^2 = .01$
R1-R2 Trial *n* × S1-R2 Trial *n* × R1-R2 Trial *n*-1 × S1-R2 Trial *n*-1	$F(1,23) = 9.11$, $p = .006$, $\eta_p^2 = .28$	$F(1,47) = 11.70$, $p = .001$, $\eta_p^2 = .20$

Appendix B: Four-way interaction pattern in Experiments 2 and 3

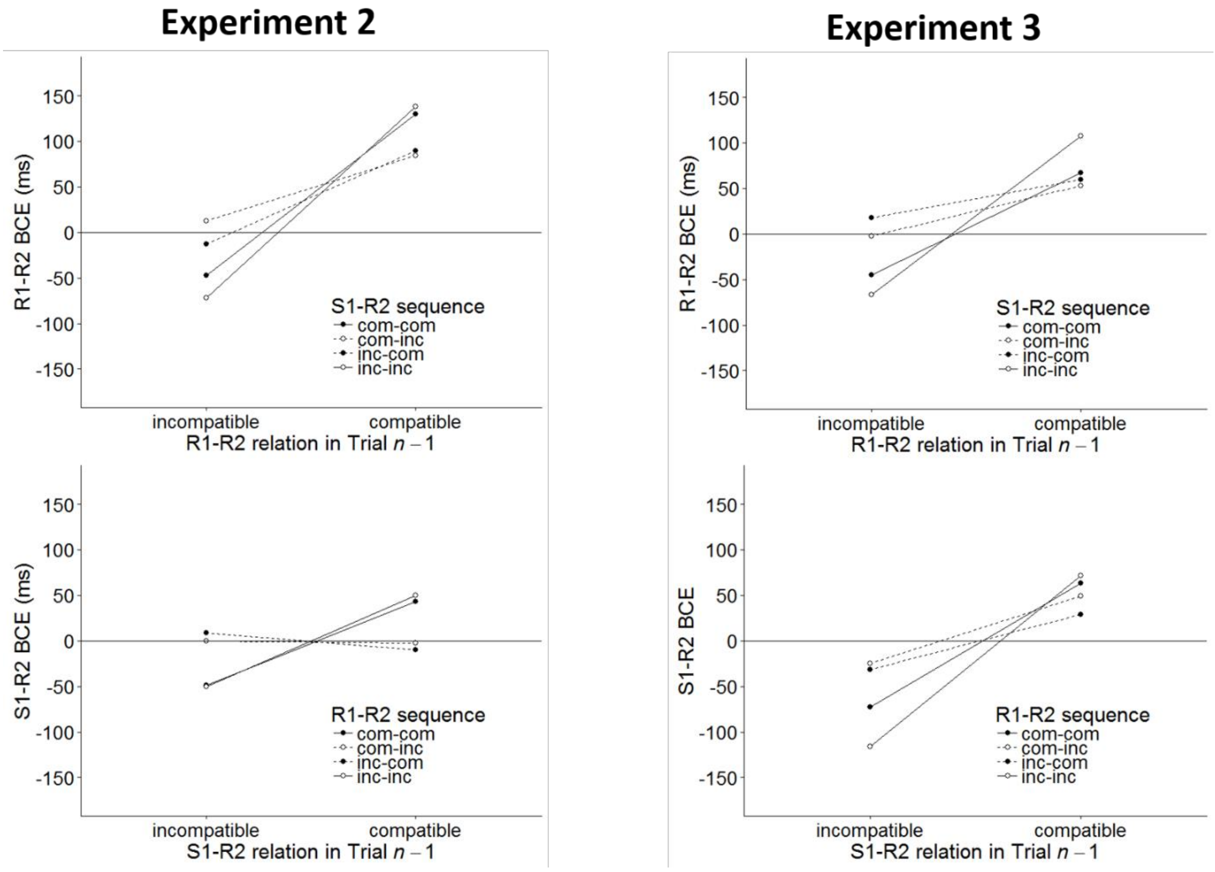

Figure B1. Within BCE sequential modulation of the R1-R2 BCE and the S1-R2 BCE in ms (incompatible minus compatible) as a function of the four possible sequences of the respective other type of BCE. The results suggest that the within BCE sequential modulations were largest when there was no simultaneous change in the other type of BCE (compare solid and dotted lines).