Acta Psychologica 188 (2018) 139–147

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

Backward crosstalk and the role of dimensional overlap within and between tasks☆

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ARTICLE INFO

Keywords:
Dual-task
Backward crosstalk
Dimensional overlap
Stimulus-response compatibility

ABSTRACT

In dual-task situations, which often involve some form of sequential task processing, features of Task 2 were shown to affect Task 1 performance, a phenomenon termed "backward crosstalk effect" (BCE). Most previous reports of BCEs are based on manipulations of code compatibility between tasks, while there is no clear picture whether and how mere Task 2 response selection difficulty (in the absence of cross-task dimensional code overlap, including effector system overlap) may also affect Task 1 performance. In the present study, we systematically manipulated response-response (R1-R2) relation (compatible, incompatible, arbitrary) and the stimulus-response (S-R) relation in Task 2 (S2-R2: compatible, incompatible, arbitrary; i.e., a classic manipulation of Task 2 response selection difficulty) to study the impact of dimensional overlap and compatibility within and across tasks using an integrated stimulus for both a vocal Task 1 and a manual Task 2. Results revealed a replication of a classic (spatial) R1-R2 compatibility BCE (based on code compatibility), demonstrating that our paradigm is principally suited to capture typical BCEs. Importantly, conditions involving a removal of dimensional code overlap between tasks still yielded an effect of mere Task 2 response selection difficulty on Task 1 performance. Both types of BCEs (i.e., BCEs based on code compatibility and BCEs based on Task 2 difficulty) could be assumed to be rooted in anticipation of response selection difficulty triggered by stimuli indicating either R1-R2 or S2-R2 incompatibility. The results are in line with recent theoretical claims that *anticipations* of response characteristics (or effects) play an important role for BCEs in particular and for conflict resolution in action control in general.

1. Introduction

Crosstalk is known as one of the major sources of interference in dual-task control (e.g., Logan & Gordon, 2001; Pashler, 1994). In a pioneering study by Navon and Miller (1987), who introduced the metaphor of crosstalk into research on elementary cognitive mechanisms, crosstalk referred to *content-based* cross-task conflict (e.g., conflict between one task requiring a "left" response and another, concurrent task requiring an incompatible "right" response). The notion of crosstalk implies that the simultaneous and parallel processing of two tasks is never fully encapsulated for each component task. Crosstalk effects can be further subdivided into forward and backward crosstalk, depending on whether features of the first task (Task 1, usually the task in which participants respond first) affect Task 2 processing or vice versa. While forward crosstalk is notoriously difficult to distinguish from other sources of interference (e.g., content-independent processing bottlenecks), previous research has demonstrated many convincing instances of backward crosstalk effects (BCE; see Lien & Proctor, 2002; Fischer & Plessow, 2015, for reviews).

1.1. Backward crosstalk

Hommel (1998) has demonstrated a BCE emerging from both stimulus- and response-related feature overlap across tasks. For example, he had participants respond to colored (red or green) letters ("S" or "H"). Color was mapped to a left/right manual key press (Task 1), letter identity to a "links"/"rechts" (German for "left"/"right") vocal response (Task 2). As a result, a significant *spatial R1-R2 compatibility BCE* emerged in Task 1 response times (RTs), with shorter RTs when both tasks required the same (vs. different) spatial response code(s). In other experiments, Hommel (1998) slightly changed the setup by mapping letter identity in Task 2 to uttering the color words "rot"/"grün" (German for "red"/"green"), thus introducing a manipulation of S1-R2 compatibility. As a result, Task 1 RTs were prolonged for incompatible

☆ Work of MJ was supported by the Institutional Strategy of the University of Tübingen (Deutsche Forschungsgemeinschaft [German Research Foundation], ZUK 63).
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https://doi.org/10.1016/j.actpsy.2018.06.004
Received 20 February 2018; Received in revised form 12 June 2018; Accepted 13 June 2018
0001-6918/

(vs. compatible) S1-R2 relations. These *BCEs* based on code overlap between tasks (either between spatial response codes across tasks or between semantic stimulus codes in Task 1 and semantic response codes in Task 2) were particularly interesting because it has previously been assumed that response-related features in Task 2 are only processed *after* response selection in Task 1 has been finished (serial response selection bottleneck: Pashler, 1994), an assumption that precludes an influence of response-related Task 2 features on Task 1 performance and that is therefore not reconcilable with these BCE phenomena. Further research has consistently replicated such BCE with different kinds of feature overlap across tasks or responses (e.g., Ellenbogen & Meiran, 2008; Hommel & Eglau, 2002; Huestegge & Koch, 2009; Lien & Proctor, 2000; Logan & Gordon, 2001; Thomson, Danis, & Watter, 2015; Watter & Logan, 2006), and even for 5- to 6-year-old children (Janczyk, Büschelberger, & Herbort, 2017) and older adults (Janczyk, Mittelstaedt, & Wienrich, 2018). The traditional explanation for this type of BCE is based on the assumption of parallel activation of response-related codes across tasks prior to response selection in the first task (i.e., in a parallel processing stage usually termed "response activation"), which either yields Task 1 processing delays due to interference between spatially incompatible codes (response code competition), or (relative) Task 1 acceleration in the case of compatible response codes due to cross-task response priming (Hommel, 1998; Lien & Proctor, 2002). Alternatively, automatic Task 2 response activation may also directly affect Task 1 response selection, similar to the flankers in a flanker task (Janczyk, Renas, & Durst, 2018; Thomson et al., 2015).

1.2. Types of backward crosstalk

However, a closer look at the literature suggests that several different types of BCEs may need to be distinguished. While in the study by Hommel (1998) crosstalk referred to cross-task conflict between two *task-relevant* codes (i.e., codes that are necessary parts of the component tasks' instructions such as spatial response features or color), subsequent research demonstrated other instances of BCE. For example, Miller and Alderton (2006) showed that instructed Task 2 response force (soft/strong in response to letter identity) affected response force in a Task 1 that only involved left/right key presses to stimulus color (i.e., without any instructions regarding response force in Task 1). This finding indicates that BCE can also affect *task-irrelevant* (non-instructed) response features, that is, features relevant only for instructions of the other, secondary task. Nevertheless, this BCE can still be conceptualized as being based on cross-task code overlap, because responses in both tasks must be executed with a particular response force even when Task 1 instructions do not explicitly refer to this.

A final interesting type of BCE has been termed "no-go BCE". Miller (2006) reported evidence that withholding responses in Task 2 in some ("no-go") trials prolonged Task 1 processing (see also Janczyk & Huestegge, 2017; Röttger & Haider, 2017). This is an interesting finding because at first sight it is not clear why any backward crosstalk could occur under such conditions: The absence of R2 should leave no room for any R2-related feature to affect Task 1 performance. One way to explain this effect is to assume that no-go trials differ from go-trials with respect to the presence of a (rather global) inhibitory process that impacts on Task 1 response processing or execution (Durst & Janczyk, 2018; Miller, 2006; see also Aron, 2011, for similar global inhibitory effects involved in stopping responses). Another possibility is that the specific *stimulus* indicating no-go trials automatically activates a "no-go" response code, which interferes with the selection of the (conceptually incompatible "go") response in Task 1. Some empirical evidence for the latter claim was provided by Röttger and Haider (2017), who demonstrated a lack of a no-go BCE in situations where no-go trials were not associated with a specific stimulus. Irrespective of the specific mechanisms, the "no go" BCEs can only be explained by referring to cross-task conflict on a more abstract level (i.e., conflict between execution and inhibition), and not by assuming cross-task conflict between more specific task-relevant (instructed) stimulus- or response-related processing codes (such as "left" and "right").

Janczyk and Huestegge (2017) followed up on the "no-go" BCE by determining the conditions under which Task 2 "no-go" demands yield performance costs or benefits in Task 1. Across a set of experiments, they manipulated whether Task 2 was a choice "go/no-go" task or a simple "go/no-go" task (the latter "go" response presumably being easier to prepare). The results suggested that a "no-go" BCE specifically occurs when Task 2 "go" responses are comparatively likely to be prepared (e.g., when the corresponding response is easy to select/configure, as in a simple RT task), subsequently requiring more inhibitory demands that negatively impact on Task 1 when compared to a less likely prepared (more difficult to select/configure) Task 2 response (as in a choice RT task). The latter case, given that there is no need for strong inhibition since there is not much to be inhibited, even yielded beneficial effects on Task 1 performance in "no go" Task 2 conditions. This observation is already first evidence that Task 2 response selection difficulty may affect Task 1 performance. However, this conclusion is rather indirect in that it refers to inhibitory processes and thus requires several (albeit plausible) assumptions, and a more direct test of the extent to which mere Task 2 response selection difficulty may affect Task 1 performance is clearly necessary.

1.3. Anticipatory processes in dual-task control

Recently, it has been proposed that *anticipation processes* may also play a major role, at least for the R1-R2 compatibility BCE. More specifically, Janczyk, Pfister, Hommel, and Kunde (2014; see also Renas, Durst, & Janczyk, 2017) studied which specific features of the second response are represented prior to or during R1 selection. They demonstrated that anticipated (visual) effects produced by R2 had a strong effect on R1 processing. These findings suggest that anticipated features of R2 (including its effects) can affect Task 1 processing relatively early in the processing chain. The impact of anticipation on dual-task control processes was further demonstrated by studies showing that mere expectation of an occasional additional task can slow down a prioritized Task 1 (e.g., Miller & Durst, 2014). Based on these considerations, it appears possible that mere anticipation of Task 2 response selection difficulty can also affect RT1 even in the absence of dimensional overlap across tasks. However, up to now there is no study which systematically addressed both the role of (spatial) R1-R2 compatibility and Task 2 (S2-R2) relation (as a typical manipulation of Task 2 response selection difficulty) on BCEs within a single, comprehensive experimental design.

1.4. Task 2 (response selection) difficulty effects

There are several previous studies involving manipulations of Task 2 (response selection) difficulty in a dual-task design. For example, a study by McCann and Johnston (1992) utilized a PRP design in which Task 1 involved vocal "high"/"low" responses to high/low tones, while response selection difficulty was manipulated in Task 2. In Experiment 1, Task 2 involved manual responses with three fingers to triangles/circles of three different sizes. As a classic manipulation of response selection difficulty, S-R mappings in Task 2 were either easy (smallest size – leftmost finger, medium size – middle finger, largest size – rightmost finger) or difficult (arbitrary mapping of stimulus size to fingers). While the authors were mainly interested in RT2 effects, they also reported a very small (5 ms) but significant effect of Task 2 response selection difficulty on RT1. However, different types of Task 2 response selection difficulty manipulations in Experiment 2 of this study did not yield significant effects on Task 1 performance. Probably, the ease of S-R translation in Task 1 (high/low tone – say "high"/"low") may have prevented consistent effects on Task 1 performance. Another drawback of this study (at least for our present purpose) is that there was (spatial) dimensional overlap across tasks since both required spatial responses (saying "high"/"low" and pressing horizontally arranged keys). Another experiment that failed to show effects of (vocal) Task 2 difficulty (Stroop task: Stroop, 1935) on (manual) Task 1 performance (key press to high/low tone) was reported by Fagot and Pashler (1992, Experiment 7). Probably, however, this experiment was somewhat underpowered (N = 12) to pick up significant effects on RT1.

More recently, two studies used a Garner interference manipulation in Task 2 (Janczyk, Franz, & Kunde, 2010; Janczyk & Kunde, 2010). Specifically, participants had to grasp an object (or respond to it with a key press) according to its width (small vs. large) while in some conditions a task-irrelevant second object dimension (object length: small vs. large) was additionally manipulated orthogonally. Task 1 consisted of key presses (or vocal responses) to high/low tones. The experiments revealed significant effects of resolving Garner interference on RT2 in the key press (but not in the grasping) version of Task 2 (suggesting a central locus of Garner interference resolution under these conditions), but there were no significant effects of Garner interference resolution on RT1. However, a comparison of the grasping version of Task 2 with the key press version (referred to as "perceptual judgement task") across blocks of trials revealed prolonged Task 1 RTs for the latter. Assuming that grasping (vs. "perceptual judgement") is usually considered easier due to the assumption of a more dorsal, automatized, overlearned control mode, this observation points to potential effects of Task 2 difficulty on Task 1 processing. However, because the design of these studies did not aim to specifically address Task 2 difficulty effects on Task 1 processing, they do not allow us to pinpoint the exact mechanisms of these effects. Taken together, these previous studies manipulating Task 2 difficulty revealed rather inconclusive results and/or utilized manipulations that may not optimally address response selection (Stroop, Garner interference), and since they were not specifically designed to address effects on Task 1 performance they are not ideally suited to answer our particular research question.

Finally, another line of studies reported a typical signature phenomenon predicted by parallel central capacity sharing models of dual-task control (e.g., Tombu & Jolicœur, 2003), which represent a theoretical alternative to the serial response selection bottleneck framework (Pashler, 1994): Increased central resource demands in Task 2 (e.g., due to a more difficult response selection) should leave fewer resources for Task 1 processing, thereby increasing Task 1 RTs. Corresponding findings were, for example, shown by Fischer, Miller, and Schubert (2007). In their Experiment 3, participants categorized digits in Task 1 as odd/even, and in Task 2 as smaller/larger than five. Importantly, numerical distance in Task 2 affected RT1: Larger numerical distance (Task 2 digits far from five) represents an easier response selection in Task 2 (compared with digits close to five) and resulted in faster Task 1 responses. A similar finding was reported by Miller (2006, Experiment 3), who showed that increased Task 2 response complexity (pressing a key one time or three times) increased RT1. However, these studies involved a common (manual) effector system across tasks, so that any interference can principally also have been enabled by the presence of dimensional overlap: "manual responses were used for both tasks […] this could be seen as a further source of between-task relatedness" (Miller, 2006, p. 486). Taken together, conclusive evidence for Task 2 response selection difficulty effects on Task 1 processing – while minimizing dimensional overlap – is still missing.

1.5. The present study

The present study addressed this research gap by systematically manipulating within-task and between-task dimensional overlap and compatibility within a single experiment based on the theoretical framework of dimensional overlap by Kornblum, Hasbroucq, and Osman (1990). These authors distinguished between element-level compatibility (e.g., whether a left stimulus is mapped to a left vs. right response, or whether a left response is required in conjunction with another left vs. right response) and set-level compatibility. The latter term is associated with the degree of dimensional (e.g., spatial) overlap between two sets of stimuli/responses (e.g., whether spatial left/right responses are required in response to spatial left/right vs. arbitrary (non-spatial) grey/white stimuli, see also Proctor & Wang, 1997). By manipulating both element-level and set-level compatibility within and across tasks, we were able to address BCE on Task 1 responses (R1) selectively due to a classic manipulation of Task 2 response selection difficulty, namely S2-R2 incompatibility (=Task 2 response selection difficulty, see also McCann & Johnston, 1992) or due to R1-R2 (in) compatibility (response code conflict). The latter effect, if present, would replicate typical BCE based on cross-task code compatibility and demonstrate that the present paradigm is principally suited to capture typical BCEs.

Specifically, we combined two tasks (a vocal Task 1 and a manual Task 2) which shared a single, multidimensional stimulus. We utilized different effector systems across tasks to avoid any strong motor-based coupling of responses across tasks and to minimize dimensional overlap regarding output systems. While the manual Task 2 response was inherently spatial (requiring a left/right key press), the vocal Task 1 response was either spatial (requiring utterances of "left"/"right", resulting in strong dimensional overlap between tasks), or arbitrary (requiring utterances of meaningless syllables, resulting in low dimensional overlap between tasks, see Huestegge, Pieczykolan, & Koch, 2014, for a similar method). This approach first allowed us to test whether R1-R2 compatibility affects Task 1 performance (replication of previous spatial response-based BCE reports). Additionally, and more interestingly, in both cases Task 2 was either S2-R2 compatible or incompatible, which allowed us to test the hypothesis that "pure" effects of Task 2 (response selection) difficulty on Task 1 performance can emerge in the absence of substantial between-task dimensional overlap. While in the case of a spatial Task 1 S2-R1 compatibility (i.e., compatibility between arrow stimuli for Task 2 and "left"/"right" utterances in Task 1) can additionally affect Task 1 performance, the most relevant condition here (to assess Task 2 difficulty effects in the absence of dimensional overlap) involves arbitrary (non-spatial) Task 1 responses. In sum, the experiment involved a fully orthogonal design (see Table 1) with the independent variables R1-R2 relation (compatible, incompatible, arbitrary) and S2-R2 relation (compatible, incompatible, arbitrary), resulting in nine experimental conditions.

2. Method

2.1. Participants

Thirty-two participants (mean age = 24.9, SD = 3.43, range: 19–33) with normal or corrected-to-normal vision volunteered in the present study. They were paid or received course credits for participation. All participants gave informed consent.

2.2. Stimuli and apparatus

Response collection and stimulus presentation were done with a standard PC connected to a 21-inch CRT screen. Experiments were programmed using Experiment Builder (SR Research, Ontario, Canada). Left/right manual key press responses were collected using two buttons on a standard keyboard (left: " < ", right: "3" on the number pad). Vocal responses were collected using the built-in voice key functionality of the Experiment Builder software (to measure RTs) and were additionally coded manually by the experimenter (to measure response errors). Visual stimuli (size: about 3.5° visual angle) were either crossed or uncrossed central arrows (i.e., arrows with or without a small vertical line at the center of the arrow) pointing to the left vs. right or a central diamond vs. square. Stimuli were always displayed using black lines on white background. The fill color of the stimulus was either

Table 1
Overview of experimental conditions (study rationale). Stimulus color (white/grey) codes the vocal Task 1 response (arbitrary: "ta"/"ko" or spatial: "left"/"right"), stimulus type (arbitrary: diamond/square or spatial: left/right arrow) codes the manual Task 2 response (left/right key press). Incompatible (vs. compatible) Task 2 S2-R2 relations are indicated by crossed (vs. uncrossed) arrows. The individual combinations of Task 1 response type (first column) and stimulus type (second column) translate into four distinct block types (A, B, C, D).

Task 1 response type	Stimulus type	R1-R2 relation	S2-R2 relation	Block
Arbitrary (non-spatial) ("ta"/"ko")	Arbitrary (diamond/square)	Arbitrary	Arbitrary	A
	Spatial (left/right arrow)	Arbitrary	Compatible (uncrossed arrow)	B
		Arbitrary	Incompatible (crossed arrow)	
Spatial ("left"/"right")	Arbitrary (diamond/square)	Compatible	Arbitrary	C
		Incompatible	Arbitrary	
	Spatial (left/right arrow)	Compatible	Compatible (uncrossed arrow)	D
		Incompatible	Compatible (uncrossed arrow)	
		Compatible	Incompatible (crossed arrow)	
		Incompatible	Incompatible (crossed arrow)	

white or grey.

2.3. Task and procedure

Each trial involved the presentation of a single, multidimensional stimulus for both tasks. The color of the stimulus (white vs. grey) indicated the required vocal Task 1 response (spatial version of Task 1: uttering the spatial words "left"/"right", non-spatial version of Task 1 with arbitrary S-R mapping: uttering the syllables "ta"/"ko"). The arrow direction (left/right) or the shape (square/diamond) indicated the required Task 2 manual left/right key press. While the square vs. diamond shape manipulation was used to establish an arbitrary S2-R2 mapping condition (i.e., with low dimensional overlap between stimuli and responses), the (spatial) arrows introduced S2-R2 dimensional overlap and thus allowed us to manipulate S2-R2 response compatibility: While uncrossed arrows indicated a key press corresponding to arrow direction (S2-R2 compatible condition, e.g., left arrow ➔ left key press), crossed arrows indicated to press the key on the opposite side (S2-R2 incompatible condition, e.g. left arrow ➔ right key press). While utilizing arrows thus enabled us to manipulate Task 2 (response selection) difficulty, the shape manipulation (square/diamond) does not allow us to manipulate Task 2 difficulty in the same way (if anything, the arbitrary S2-R2 mapping in Task 2 might even be more difficult than an incompatible S2-R2 mapping), and simply served as an additional baseline to further interpret the effects of S2-R2 compatibility on Task 1. Table 1 presents an overview of the design rationale, and Fig. 1 depicts all specific stimulus-response combinations.

Each trial started with the presentation of a central fixation cross (300 ms) followed by the central visual stimulus, which remained on the screen until both responses were executed. Instructions highlighted both speed and accuracy as well as response order (vocal Task 1 responses were to be executed prior to manual Task 2 responses). Response feedback was only provided in the case of an incorrect response order. For familiarization purposes, 16 training trials (not further analyzed) were presented whenever a new block type was introduced to the participant.

The assignment of colors to vocal responses and the assignment of shape (square/diamond) to manual responses were counterbalanced across participants (resulting in 4 different S-R mapping combinations). The individual combinations of Task 1 response type (spatial vs. arbitrary) and stimulus type (spatial vs. arbitrary) translate into four distinct block types (A, B, C, D). Each block type was presented four times with each block involving 32 trials presented in randomized order. More specifically, Task 2 stimulus type (arrow vs. square) changed after half of the experiment, while in each half the two block types were presented twice in an alternating sequence (e.g., AA, BB, AA, BB, CC, DD, CC, DD for one participant, block type order counterbalanced across participants). Each block started with a reminder of the instructed S-R mappings for both tasks.

2.4. Design and analyses

RTs and error rates for vocal and manual responses were measured as dependent variables. While the overall rationale of the conceptual design corresponds to a full factorial 3 (R1-R2-Relation: arbitrary, compatible, incompatible) by 3 (S2-R2 Relation: arbitrary, compatible, incompatible) design (see Table 1), statistical analyses need to account for the differences in stimulus type and Task 1 response type across blocks, that is, task conditions across the four block types are not directly comparable. Thus, we analyzed each block type separately except for a combined analysis of the two blocks involving arbitrary Task 1 responses. While these latter two blocks still differed with respect to stimulus type (left/right arrow vs. diamond/square), we reasoned that at least RT1 is largely comparable (same vocal "ta"/"ko" responses to white/grey stimulus color). Each result section will start with a Task 1 report (i.e., RTs/error rates for vocal responses) due to the focus on BCEs, followed by the corresponding Task 2 (manual response) analyses. In the case of sphericity violations Greenhouse-Geisser corrected p-values are reported.

3. Results

First, we removed all trials with RTs < 150 ms and/or trials lacking the required responses from further analysis (overall 3.7%, range across the nine conditions: 2%–6%). For RT analyses, we only included error-free trials. To rule out the possibility that specific response strategies (e.g., grouping) affect the pattern of results (e.g., Ulrich & Miller, 2008), we used two strategies of RT data analysis: first, an unconstrained analysis including all valid RT data, and second, a constrained analysis without inter-response intervals < 100 ms and without outlier RTs exceeding 3 SDs per condition and participant (together constituting 6.9% of the valid RT data). Since a comparison of the results between both types of analysis only revealed very minor differences in means (and no differences regarding the patterns of significance whatsoever), the following RT reports are based on the unconstrained analysis only. Task 1 performance data are visualized in Figs. 2–4; Task 2 performance data are summarized in Table 2.

3.1. Arbitrary (non-spatial) Task 1

Results in this condition (Fig. 2) were analyzed using a one-way ANOVA with the factor S2-R2 Compatibility (compatible, incompatible, arbitrary) as a repeated-measure.

3.1.1. Task 1 (vocal)

The analysis of RT1 revealed a significant effect of S2-R2 Compatibility, $F(2, 62) = 10.13$, $p = .001$, $\eta_p^2 = 0.25$. Post hoc contrasts (LSD) revealed a significant difference between compatible (M = 887 ms, SE = 25) and incompatible (M = 932 ms, SE = 29) conditions, $p < .001$, between compatible and arbitrary (M = 960 ms,

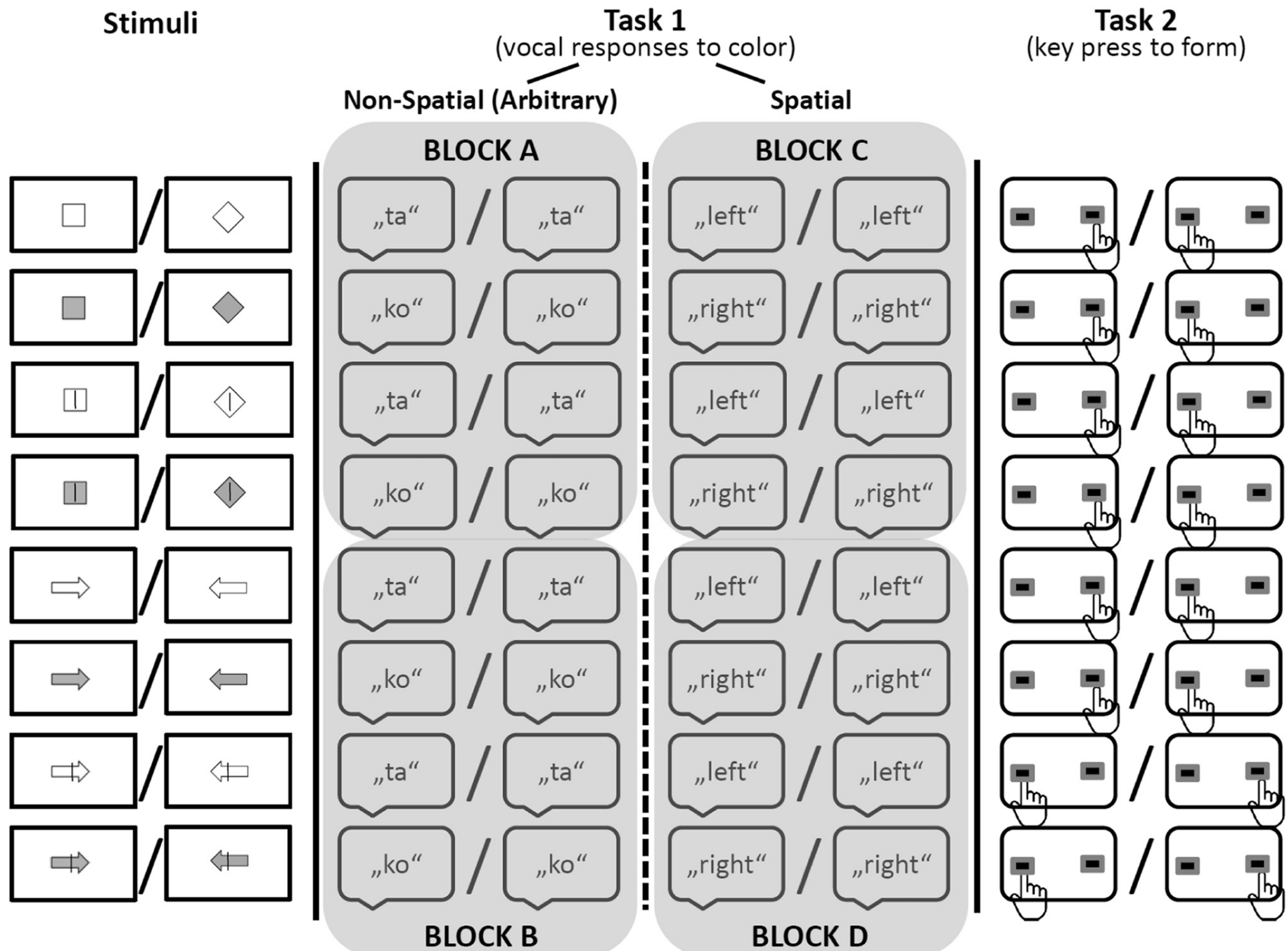

Fig. 1. Overview of stimuli and responses for the various task combinations. In the lower four lines, crossed-out arrows indicate spatially incompatible Task 2 S2-R2 mappings. In the upper four lines, Task 2 S2-R2 mappings are arbitrary throughout, thus crossed-out stimuli were only included for the sake of comparability (i.e., the crossed line in these conditions did not reverse the S2-R2 mapping to create S2-R2 incompatible conditions as was the case for arrow stimuli).

SE = 23) conditions, p = .001, but not between incompatible and arbitrary conditions, p = .146. Error rates in Task 1 were very low (compatible: M = 1.2%, SE = 0.5, incompatible: M = 1.6%, SE = 0.4, arbitrary: M = 3.5, SE = 1.0). The general direction followed that of RT1, but there was no significant effect of S2-R2 Compatibility, F(2, 62) = 3.65, p = .058. Given this marginally significant effect, we followed up with a post-hoc contrast regarding the important compatible vs. incompatible conditions, which was clearly non-significant, $t < 1$.

3.1.2. Task 2 (manual)

The analysis of RT2 also revealed a significant effect of S2-R2 Compatibility, F(2, 62) = 16.98, p < .001, $\eta_p^2 = 0.354$. Post hoc contrasts (LSD) revealed a significant difference between compatible (M = 1207 ms, SE = 33) and incompatible (M = 1261 ms, SE = 36) conditions, p < .001, between compatible and arbitrary (M = 1327 ms, SE = 33) conditions, p < .001, and between incompatible and arbitrary conditions, p = .013. Note that any comparison in Task 2 performance with the arbitrary condition should be treated carefully, since this condition involved another type of stimulus (square/diamond) than the other conditions (arrow). Error rates in Task 2 were very low, too (compatible: M = 2.0%, SE = 0.6, incompatible: M = 1.0%, SE = 0.5, arbitrary: M = 2.9, SE = 0.8), and there was no significant effect of S2-R2 Compatibility, F(2, 62) = 2.62, p = .078.

3.2. Spatial Task 1 in the context of an arbitrary S2-R2 relation

Results in this condition (Fig. 3) were analyzed using paired sample *t*-tests (R1-R2 Compatibility: compatible vs. incompatible).

3.2.1. Task 1 (vocal)

RT1 was shorter in R1-R2 compatible (M = 927 ms, SE = 28) than in R1-R2 incompatible (M = 971 ms, SE = 24) conditions, t(31) = 3.94, p < .001, indicating a BCE purely based on R1-R2 compatibility. Error rates in Task 1 did not differ significantly (R1-R2 compatible: M = 3.2%, SE = 0.2, R1-R2 incompatible: M = 3.9%, SE = 0.1), t(31) = 1.32, p = .198.

3.2.2. Task 2 (manual)

RT2 was also shorter in R1-R2 compatible (M = 1348 ms, SE = 47) than in R1-R2 incompatible (M = 1407 ms, SE = 44) conditions, t(31) = 3.67, p = .001. Error rates in Task 2 did not differ significantly (R1-R2 compatible: M = 2.1%, SE = 0.6, R1-R2 incompatible: M = 2.8%, SE = 0.7), t(31) = 1.02, p = .316.

3.3. Spatial Task 1 in the context of a compatible/incompatible S2-R2 relation

Results in this condition (Fig. 4) were analyzed using 2 × 2 repeated measurement ANOVAs (R1-R2 Compatibility: compatible vs. incompatible, S2-R2 Compatibility: compatible vs. incompatible).

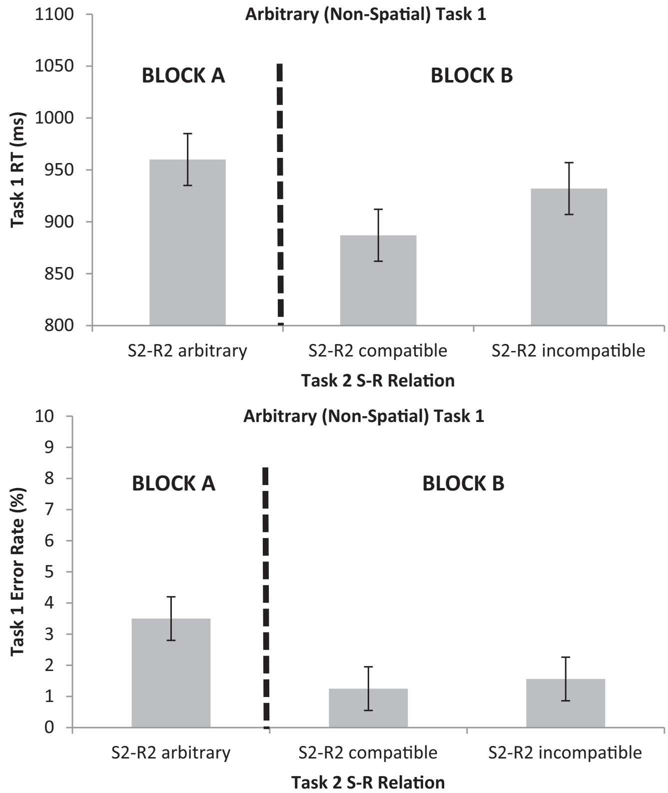

Fig. 2. Task 1 response times (upper panel) and error rates (lower panel) in conditions involving an arbitrary (non-spatial) Task 1 (error bars represent SE).

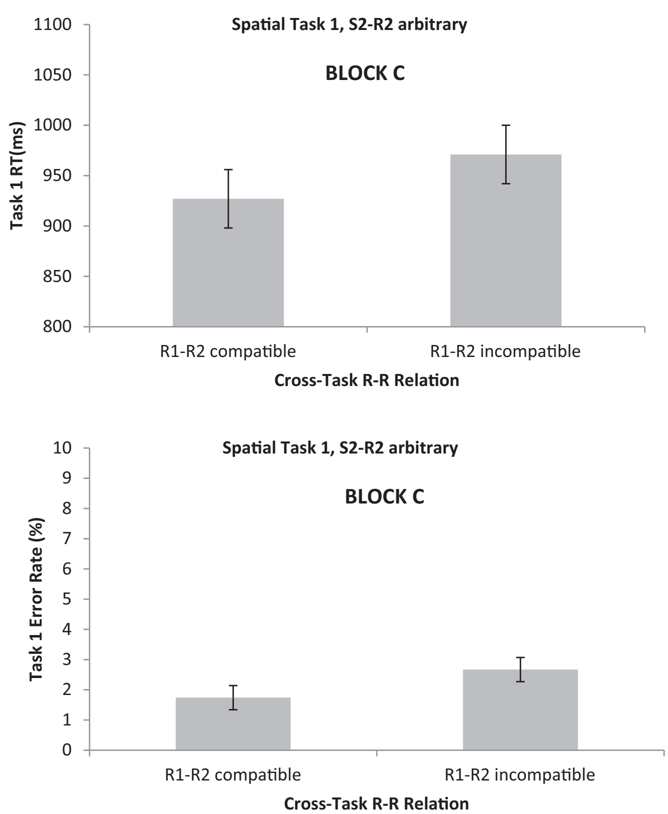

Fig. 3. Task 1 response times (upper panel) and error rates (lower panel) in conditions involving a spatial Task 1 and an arbitrary S2-R2 assignment in Task 2 (error bars represent SE).

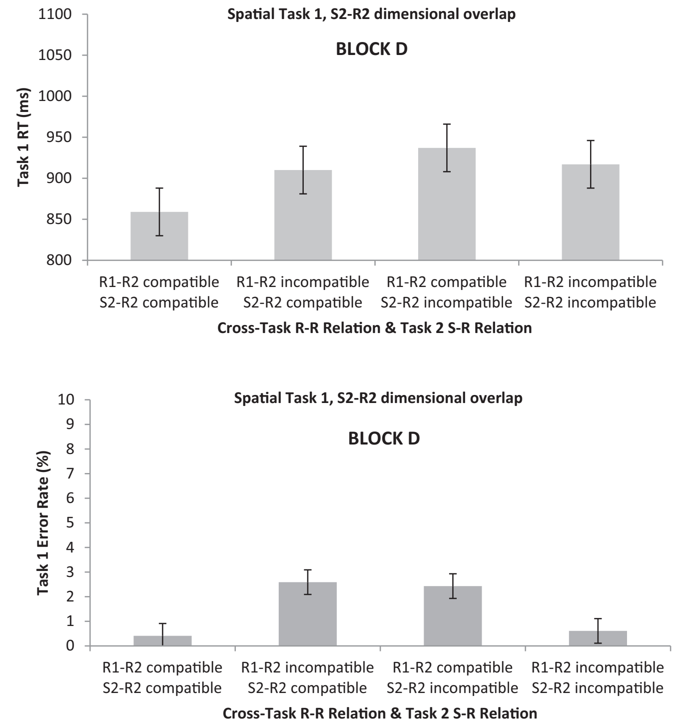

Fig. 4. Task 1 response times (upper panel) and error rates (lower panel) in conditions involving a spatial Task 1 and a spatial (compatible vs. incompatible) S2-R2 assignment in Task 2 (error bars represent SE).

3.3.1. *Task 1 (vocal)*

The analysis of RT1 revealed no significant main effect of R1-R2 Compatibility, $F(1, 31) = 3.36$, $p = .077$, $\eta_p^2 = 0.10$, but a significant main effect of S2-R2 Compatibility, $F(1, 31) = 19.22$, $p < .001$, $\eta_p^2 = 0.38$, and a significant interaction, $F(1, 31) = 15.99$, $p < .001$, $\eta_p^2 = 0.34$. This interaction can be interpreted from two perspectives: First, there is only a significant R1-R2 Compatibility effect in the S2-R2 compatible condition (50 ms, $p = .001$), but not in the S2-R2 incompatible condition (−20 ms, $p = .053$). Second, there is only a significant S2-R2 compatibility effect in R1-R2 compatible conditions (78 ms, $p < .001$), but not in R1-R2 incompatible conditions (7 ms, $p = .620$). Visual inspection of Fig. 4 indicates that the interaction is mainly driven by an RT1 advantage in fully compatible (i.e., R1-R2 and S2-R2 compatible) conditions, while the combination of both types of incompatibility clearly has an under-additive effect on RT1.

With respect to Task 1 error rates, we did not observe significant main effects of R1-R2 Compatibility or S2-R2 Compatibility, $Fs < 1$, but a significant interaction, $F(1, 31) = 12.27$, $p = .001$, $\eta_p^2 = 0.28$. Similar to the RT data, there was only a significant R1-R2 Compatibility effect in the S2-R2 compatible condition (2.2 percentage points, $p = .018$). However, there was a reversed R1-R2 Compatibility effect in the S2-R2 incompatible condition (−1.8 percentage points, $p < .001$). Second, there was only a significant S2-R2 Compatibility effect in the R1-R2 compatible condition (2.0 percentage points, $p < .001$), but a reversed S2-R2 Compatibility effect in R1-R2 incompatible condition (−2.0 percentage points, $p = .020$). Similar to the RT1 data, we thus found no indication for additive performance decrements when both types of spatial (R1-R2 and S2-R2) incompatibility were present, but instead a reversed pattern (i.e., a relative performance advantage in this particular condition).

3.3.2. *Task 2 (manual)*

The analysis of RT2 revealed a significant main effect of R1-R2 Compatibility, $F(1, 31) = 6.28$, $p = .018$, $\eta_p^2 = 0.17$, a significant main effect of S2-R2 Compatibility, $F(1, 31) = 27.39$, $p < .001$, $\eta_p^2 = 0.47$,

Table 2
Mean Task 2 response times and error rates (SE in parentheses).

Task 1 response type	Stimulus type	R1-R2 relation	S2-R2 relation	Block	RT (ms)	Error rate (%)
Arbitrary (non-spatial)	Arbitrary	Arbitrary	Arbitrary	A	1327 (33)	2.87 (0.8)
	Spatial	Arbitrary	Compatible	B	1207 (33)	2.01 (0.6)
		Arbitrary	Incompatible		1261 (36)	0.99 (0.5)
Spatial	Arbitrary	Compatible	Arbitrary	C	1348 (47)	2.12 (0.4)
		Incompatible	Arbitrary		1407 (44)	2.77 (0.4)
	Spatial	Compatible	Compatible	D	1238 (42)	1.68 (0.7)
		Incompatible	Compatible		1313 (41)	6.69 (1.4)
		Compatible	Incompatible		1348 (42)	1.43 (0.5)
		Incompatible	Incompatible		1316 (42)	1.50 (0.7)

and a significant interaction, $F(1, 31) = 25.209$, $p < .001$, $\eta_p^2 = 0.45$. Visual inspection of Fig. 3 shows that the overall pattern of RT2 closely resembles the pattern of RT1 (see above).

Task 2 error rate analyses also revealed a significant main effect of R1-R2 Compatibility, $F(1, 31) = 18.87$, $p < .001$, $\eta_p^2 = 0.378$, a significant main effect of S2-R2 Compatibility, $F(1, 31) = 16.81$, $p < .001$, $\eta_p^2 = 0.352$, and a significant interaction, $F(1, 31) = 15.58$, $p < .001$, $\eta_p^2 = 0.33$. Again, the Task 2 error rate effects are mainly driven by especially high error rates for the combination of R1-R2 incompatible and S2-R2 compatible conditions, while error rates are lowest when either both types of compatibility were present (R1-R2 and S2-R2 compatibility) or absent (R1-R2 and S2-R2 incompatibility).

4. Discussion

In order to study the impact of dimensional overlap and compatibility within and across tasks on the BCE, we ran a dual-task experiment with a single, multidimensional stimulus coding responses for both a vocal Task 1 and a manual Task 2. Crucially, we systematically manipulated the R1-R2 relation (compatible, incompatible, arbitrary) and the S2-R2 relation (compatible, incompatible, arbitrary). While previous BCE studies mainly focused on the contrast between compatible and incompatible R1-R2 relations (*R1-R2 compatibility BCE*), our present design also allows us to assess the impact of Task 2 response selection difficulty (*Task 2 response selection difficulty BCE*) under various degrees of dimensional overlap within and across tasks. The two main results were straightforward:

1. The contrast between S2-R2 compatible and incompatible relations on arbitrary (non-spatial) Task 1 responses indicates a BCE based on Task 2 response selection difficulty (*Task 2 response selection difficulty BCE*). While the additional arbitrary condition is not perfectly comparable due to the different stimuli, a careful interpretation of this condition in terms of a baseline suggests an advantage of compatibility rather than a disadvantage of incompatible spatial S2-R2 mappings on RT1. This finding is to some extent similar to previous reports of a Task 2 difficulty effect on RT1. For example, there was an increased RT1 across blocks of trials when Task 2 involved a perceptual judgement key press (vs. grasping) in the Garner interference task (Janczyk et al., 2010; see also Janczyk & Kunde, 2010). However, it should be noted that implementing these two versions of a Garner interference task does not represent a classic, selective manipulation of response selection difficulty. The present results are also in line with results in Experiment 1 of McCann and Johnston (1992), who used a similar classic response selection difficulty manipulation as in the present study. However, their effect was only very small (5 ms) and did not replicate in their second (principally comparable) experiment. Furthermore, their setup still involved dimensional overlap between tasks (both tasks required spatial responses), which may also have contributed to the observed effect in their Experiment 1. The present results are also in line with other demonstrations of Task 2 response selection difficulty effects on Task 1 processing (e.g., Fischer et al., 2007; Miller, 2006), but our present results demonstrate that these effects can also be found under minimized cross-task dimensional overlap (including the utilization of different effector systems across tasks). Thus, the demonstration of a pure Task 2 response selection difficulty effect on Task 1 performance (in the absence of dimensional overlap between tasks) in the present study is a novel finding.

Two explanations of this effect are principally conceivable. First, any instance of an effect of Task 2 difficulty on Task 1 processing can be considered a classic indicator for central capacity sharing accounts of dual-task control (e.g., Tombu & Jolicoeur, 2003). Specifically, such models assume that a more difficult Task 2 should draw resources away from Task 1 processing, thus yielding less efficient processing in the latter. However, a drawback of this plausible mechanism (resource shift due to a change in the difficulty gradient between tasks) is that it cannot by itself also account for the other type of effect on RT1 found in our results, the classic R1-R2 compatibility BCE (see below): The R1-R2 compatibility BCE is based on the relation of codes between two component tasks which (individually) do *not* change in terms of their difficulty.[1] To provide a single (and thus more parsimonious) mechanism for *both* types of effects on RT1, we thus rather prefer another explanation of the Task 2 difficulty effect: We assume that the anticipated Task 2 difficulty (based on early processing of the stimulus dimension relevant for Task 2, specifically, the vertical line on top of the arrow) may yield a more careful, slower overall task processing (general slowing) which also affects Task 1 (i.e., the anticipation of a more difficult and thus slower R2 affects R1 processing). The idea that anticipations of R2-related features affect Task 1 processing is in line with recent theoretical claims (Janczyk et al., 2014) and corresponding empirical data showing that also other R2-related anticipations (specifically the perceptual effects of R2) impact on Task 1 processing. The present results further extend these previous observations by showing that not only *intended* R2-related anticipations (i.e., the action goals), but also other anticipated R2 features can affect Task 1 processing. Conceptualized in this way, it still appears valid to refer to the notion of crosstalk for this special case of a BCE. The assumption that the relevant Task 2 anticipations are based on the presence of the respective stimulus (vertical line) is nicely in line with findings from Röttger and Haider (2017), suggesting that specific Task 2 stimuli associated with certain response features can automatically activate representations that affect Task 1 processing. Converging evidence has also been

[1] Note that typical resource sharing models (e.g., Tombu & Jolicoeur, 2003) are of course actually better suited to allow for the occurrence of crosstalk effects than are bottleneck models (e.g., Pashler, 1994) because of their assumption of parallel processing, which is a prerequisite for crosstalk effects to occur. However, the actual phenomenon of crosstalk requires an *additional* mechanism (e.g., code priming/interference) apart from a resource allocation shift based on a change in the difficulty gradient between tasks. Thus, the notion of capacity sharing (based on relative difficulty of the two component tasks) *in itself* cannot explain content-based interference (crosstalk) effects, even though such effects can principally affect stage durations of the component tasks and thereby affect resource allocation.

reported by Miller (2017), who focused on lateralized readiness potentials (LRPs) in a BCE paradigm. His results suggested that BCEs arise because Task 2 stimuli influence response selection in Task 1 rather than because Task 2 stimuli activate the Task 2 responses with which they are associated.

2. The significant difference in RT1 as a function of R1-R2 compatibility – in the absence of any strong dimensional overlap between stimuli and responses within both tasks – is a replication of a classic *R1-R2 compatibility BCE* indicating cross-task response-related conflict (Hommel, 1998). The finding of this type of BCE is consistent with many previous BCE studies that were conducted with different kinds of feature overlap across responses (e.g., Hommel & Eglau, 2002; Lien & Proctor, 2000; Logan & Gordon, 2001) and are consistent with previous reports that this type of BCE also occurs when the stimuli for both tasks are part of the same object (Ellenbogen & Meiran, 2008; Hommel, 1998). A basic explanation for this type of BCE is that the parallel activation of response codes across tasks (prior to response selection in the first task; Hommel, 1998; Lien & Proctor, 2002; but see Janczyk, Renas et al., 2018; Thomson et al., 2015) yields processing delays due to interference between spatially incompatible codes (response code competition), while compatible response codes may yield (relative) priming advantages (see Hommel, 1998). However, in light of the aforementioned framework of explaining BCEs with respect to anticipatory processes (Janczyk et al., 2014) it is also possible to assume that mere anticipation of incompatibility (e.g., of response features/effects) in a trial (as indicated by the stimulus features) is already sufficient to generally slow down task processing, a mechanism that also affects Task 1 RTs. In any case, the replication of a classic BCE based on response code conflict demonstrates that our present paradigm is generally suited to capture typical BCE.

4.1. Limitations and an agenda for future research

The analyses of conditions involving spatial stimuli and spatial responses for both tasks are basically in line with both an instance of *Task 2 difficulty BCE* (under R1-R2 compatible conditions) and an instance of *spatial R1-R2 compatibility BCE* (under S2-R2 compatible conditions). Note, however, that it is difficult to come up with a clear interpretation of the interaction of the two types of BCE. Specifically, the results show an under-additive effect when both types of incompatibility (S2-R2 incompatibility and R1-R2 incompatibility) co-occur. Performance here is roughly at the same level as in conditions where only one type of incompatibility is present (with respect to RT1), or tends to be slightly better (with respect to error rates). Several explanations are conceivable for this under-additivity. First, it is possible to interpret these findings in terms of an absence of an R1-R2 compatibility BCE when Task 2 is S2-R2 incompatible. This might indicate strategic shielding of Task 1 (e.g., Fischer & Hommel, 2012; Janczyk, 2016) when tasks are conceptually related (due to cross-task dimensional overlap) and when Task 2 is anticipated to become difficult (e.g., when participants perceive the crossed arrow indicating an incompatible S2-R2 mapping). This reasoning would be in line with capacity sharing theories of dual-task control (e.g., Tombu & Jolicoeur, 2003). According to this theory, a difficult Task 2 might draw resources away from an easier Task 1, which might eventually translate into smaller crosstalk effects on Task 1. There is robust empirical evidence that anticipating the expected degree of conflict (or the expected amount of temporal task overlap) can reduce backward crosstalk. Such bottom-up priming of shielding is elicited by contexts (such as locations at which items are presented) or by specific Task 1 stimuli that are predictive of specific SOA levels (Fischer & Dreisbach, 2015; Fischer, Gottschalk, & Dreisbach, 2014).

Another plausible explanation for the absence of an (over)additive effect for both types of crosstalk refers to the compatibility relation between S2 and R1. Specifically, the two conditions involving either R1-R2 incompatibility or S2-R2 incompatibility (but not both at the same time) necessarily involve S2-R1 incompatibility, while the condition involving both R1-R2 and S2-R2 incompatibility necessarily involves S2-R1 compatibility. Thus, the beneficial effect of S2-R1 compatibility may have simply cancelled out the adverse effect of the presence of both R1-R2 and S2-R2 incompatibility. Please note that within the present research logic it is not possible to come up with a research design that avoids the co-variation between S2-R1 compatibility and the presence of both R1-R2 and S2-R2 incompatibility. However, since the main focus of the present paper is on the demonstration of different BCE types, not on their interaction, we suggest that the interplay between the BCE types should be addressed in a dedicated future series of experiments using a different implementation of response selection difficulty (e.g., by varying the number of response alternatives).

The present study examined two types of crosstalk by utilizing an experimental setup requiring cross-modal responses in the manual and vocal domain. This was done to further minimize dimensional overlap in terms of common associated effector systems across tasks. We suggest that taking shared vs. different effector systems into account when explaining dual-task costs might be of vital importance. It was assumed that assigning a selected response code (e.g., "left") to a certain effector system (e.g., "left index finger") could represent an important additional stage in task processing that was previously neglected, and which might represent a further potential locus of crosstalk (Huestegge et al., 2014). Previous research has demonstrated that while on a general level crosstalk is a rather universal phenomenon within and across input and output systems, the specific impact of crosstalk manipulations can vary as a function of effector systems (Huestegge, 2011; Huestegge & Adam, 2011; Huestegge & Hazeltine, 2011; Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014, 2017, 2018; Stephan, Koch, Hendler, & Huestegge, 2013). Thus, it would be theoretically informative to study the dependency of the two types of crosstalk on different combinations of output systems in future research.

4.2. Conclusion

In sum, the present study demonstrates that it is vital to consider dimensional overlap (Kornblum et al., 1990; Proctor & Wang, 1997) in the context of explaining the underlying mechanisms of BCEs. By systematically manipulating dimensional overlap and compatibility we were able to replicate a classic spatial R1-R2 compatibility BCE and to demonstrate a BCE based on Task 2 response selection difficulty in the absence of dimensional overlap across tasks. Despite the possibility of assuming two distinct explanations for these two effects on Task 1 (namely cross-task code conflict/priming and capacity allocation shifts based on component task difficulty), both BCEs appear to be in line with a more parsimonious unified account assuming anticipation of task processing difficulty. This would be in line with recent claims that anticipations of response features/effects (here: anticipation of response selection difficulty triggered by stimuli indicating either R1-R2 or S2-R2 incompatibility) play an important role for BCEs in particular and for conflict resolution in action control in general. We are confident that the present findings represent an important step in the direction of a more complete understanding of the various mechanisms underlying crosstalk in cognition.

Funding

This study (MJ's part) was partially funded by the Institutional Strategy of the University of Tübingen (Deutsche Forschungsgemeinschaft [German Research Foundation], ZUK 63).

Conflict of interest

All authors (LH, AP, and MJ) declare that they have no conflict of interest.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. This article does not contain any studies with animals performed by any of the authors.

Informed consent

Informed consent was obtained from all individual participants included in the study.

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