

# Sources of interference in cross-modal action: response selection, crosstalk, and general dual-execution costs

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**Abstract** Performing several actions simultaneously usually yields interference, which is commonly explained by referring to theoretical concepts such as crosstalk and structural limitations associated with response selection. While most research focuses on dual-task scenarios (involving two independent tasks), we here study the role of response selection and crosstalk for the control of cross-modal response compounds (saccades and manual responses) triggered by a single stimulus. In two experiments, participants performed single responses and spatially compatible versus incompatible dual-response compounds (crosstalk manipulation) in conditions with or without response selection requirements (i.e., responses either changed randomly between trials or were constantly repeated within a block). The results showed that substantial crosstalk effects were only present when response (compound) selection was required, not when a pre-selected response compound was merely repeated throughout a block of trials. We suggest that cross-response crosstalk operates on the level of response selection (during the activation of response codes), not on the level of response execution (when participants can rely on pre-activated response codes). Furthermore, we observed substantial residual dual-response costs even when neither response incompatibility nor response selection requirements were present. This suggests additional general dual-execution interference that occurs on a late, execution-related

processing stage and even for two responses in rather distinct (manual and oculomotor) output modules. Generally, the results emphasize the importance of considering oculomotor interference in theorizing on multiple-action control.

## Introduction

While the cognitive approach to the study of human behavior is typically characterized by controlled experiments involving basic, isolated actions such as manual key press responses (see Baumeister, Vohs, & Funder, 2007), actual human behavior is more complex in that it usually involves multiple actions at a time. In fact, it involves often across several effector systems including the oculomotor system. Usually, the execution of multiple (vs. single, isolated) actions is associated with performance costs in terms of increased response times (RTs) and error rates. Such costs are mostly studied in the context of dual-task research, where two responses are required that are each triggered by a separate stimulus (or discernible stimulus dimension). Correct performance can only be achieved by attending to both stimuli and by applying the stimulus–response (S–R) translation rules associated with each task (e.g., Pashler, 1994). However, multiple-action control can also be studied in an experimental setup in which one single stimulus (aspect) defines two responses (*single-onset paradigm*)—a situation that has been described as resembling a single-task situation requiring the selection of a *response compound* (Fagot & Pashler, 1992). The present study utilizes the single-onset paradigm to analyze the simultaneous execution of manual and oculomotor actions (two fairly distinct, but inherently spatial output systems) with the aim to shed more light on basic mechanisms

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underlying the control of such cross-modal response compounds, namely response selection (RS) and crosstalk. This also allows us to examine whether the underlying interference mechanisms necessarily require some of the features typically characterizing dual-task situations (e.g., two distinct task processing streams, response selection requirements).

From a theoretical point of view, it is particularly interesting to study the interaction of those output systems that permanently need to be coordinated in real-life but are only rarely considered in empirical research and in theory on multiple-action control: manual and oculomotor actions. Specifically, oculomotor control is mostly only regarded as a means to ensure optimal visual input for task control (i.e., as a mere prerequisite or indicator of visual attention), but not as an action domain in its own right that may interact with other motor domains (Huestegge, 2011; Huestegge & Hazeltine, 2011). This blind spot is especially surprising since attention research has often emphasized the close relationship between visual attention and oculomotor control, culminating in the view that crucial aspects of visual attention shifts may largely be equated with oculomotor preparation (e.g., Huestegge & Koch, 2010; Schneider & Deubel, 2002; Rizzolatti, Riggio, Dascola, & Umiltà, 1987). For example, the EPIC multitasking framework (Meyer & Kieras, 1997) explicitly includes an ocular motor processor unit “for moving EPIC’s eyes, whose spatial position determines what inputs may enter the visual perceptual processor” (p. 15). However, the mechanisms underlying the potential interactions of this ocular motor processor with other motor systems remained unspecified in EPIC. Hence the present study represents a further step towards closing this research gap. Our results will be informative regarding action-related sources of interference typically envisioned in theories focusing on interactions between parallel action demands (e.g., Navon & Miller, 2002; Tombu & Jolicœur, 2003), but with a focus on oculomotor control.

### Response selection

The concept of *response selection* can be traced back to a pioneer of the study of “mental mechanics”, Donders (1869), and was initially developed in the context of single-task processing. The crucial assumption is that whenever more than one response is task-relevant across a sequence of trials, a time-consuming decision process becomes necessary to select the appropriate response (among alternatives) based on (S–R) rules, eventually prolonging overall RTs. Note that this idea of RS as a time-consuming mental processing stage is essentially a structural account and does not inherently depend on the particular task content (e.g., the specific response characteristics) that

needs to be processed. Long after Donders (1869), the notion of RS was revitalized by Pashler (1994), who suggested that this particular mental process (unlike other mental processes such as stimulus identification or response execution) cannot occur for two tasks at the same time, thus constituting a central limitation of the human mind. Evidence for the idea that two RS processes must be carried out serially comes from a large amount of dual-task studies employing the psychological refractory period (PRP) paradigm. In the PRP paradigm, the temporal overlap between two tasks is manipulated by varying the onset of the stimuli, that is, the stimulus onset asynchrony (SOA). Usually, for short SOAs Task 2 RTs increase when compared to long SOAs, suggesting that RS processing of Task 2 has to wait until RS processing of Task 1 is finished. Note that in these dual-task studies *two distinct* RS processes are required in each trial, one for each task.

Another less frequently used paradigm to study RS for dual responses is the *single-onset paradigm*, in which one aspect of a stimulus triggers both responses. For example, Holender (1980) asked participants to respond to visual letters with either a button press response, a vocal naming response, or both (i.e., as a dual-response compound). A comparison of single- and dual-response times for vocal responses revealed dual-response costs (i.e., longer RTs in dual-response conditions than in single-response conditions), while no costs were observed for manual responses. This result pattern has been replicated by Fagot and Pashler (1992), who additionally manipulated S–R compatibility in the manual task across several experiments. Based on their pattern of results, they concluded that the single-onset paradigm yields one common, compound RS process (thus resembling a single task).

### Crosstalk

Unlike the notion of response selection, the concept of *crosstalk* has been suggested to account for interference effects that are specifically related to task content. In the case of response compounds, crosstalk effects typically refer to beneficial effects of spatially compatible (vs. incompatible) component responses. However, crosstalk effects were originally established in the context of dual-task research: When two temporally overlapping tasks involve conflicting codes (e.g., Task 1 requires a “left” response, and Task 2 requires a “right” response), RTs in the two tasks are usually increased when compared to a situation without conflicting (e.g., spatially compatible) codes. Especially the RT increase in Task 1 (usually referred to as *backward crosstalk*) has received considerable attention, since it suggests that response-related processing in Task 2 already affects response-related processing in Task 1 (e.g., Ellenbogen & Meiran, 2010;

Hommel 1998; Janczyk, Pfister, Hommel, & Kunde, 2014; Logan & Schulkind, 2000; Miller, 2006; Miller & Alderton, 2006; Thomson, Watter, & Finkelshtein, 2010). This finding is typically explained by assuming parallel activation of response features. Specifically, response features are assumed to be automatically activated with the appearance of the stimulus based on previously established S–R links (Hommel, 1998; see also Janczyk, 2016; Watter & Logan, 2006) and, therefore, allow crosstalk to occur between the two tasks. Dependent on response compatibility, response activation in Task 2 exerts crosstalk effects on response activation in Task 1. Finally, this effect is assumed to propagate onto Task 2 processing time (indirect influence model, see Lien & Proctor, 2002; Schubert, Fischer, & Stelzel, 2008).

Comparatively less is known about crosstalk in response compounds, that is, in situations not necessarily requiring two independent RS processes. A first step towards filling this gap was made by Huestegge and Koch (2009, 2010), who utilized a single-onset paradigm involving oculomotor–manual response compounds. Specifically, a left/right auditory stimulus triggered either one or two responses. Dual-response costs, that is, the difference between RTs in single and dual-response blocks, served as the crucial marker for the amount of interference between the two responses within the dual-response compound. In their first study (Huestegge & Koch, 2009), spatial compatibility between two responses was systematically manipulated by instructing participants to execute R–R compatible responses (e.g., both responses on the right) or R–R incompatible responses (e.g., saccade to the left and manual keypress on the right). Interestingly, they found increased dual-response costs in R–R incompatible compounds compared to R–R compatible compounds. These results are first evidence that crosstalk does not rely on the presence of two distinct task processing streams in a trial.

In a subsequent work, Huestegge and Koch (2010) aimed at specifying the mechanisms of response-related crosstalk with respect to the influence of temporal response distance. Again utilizing saccades and manual responses in a single-onset setup, they contrasted dual-response costs in a condition with S–R compatible saccades and S–R incompatible manual responses with those in a condition with S–R incompatible saccades and S–R compatible manual responses. Interestingly, while in the former condition responses were executed with a larger temporal distance than in the latter, overall dual-response costs remained unchanged. Thus, R–R crosstalk effects were unaffected by temporal response distance (see also Pieczykolan & Huestegge, 2014) suggesting that responses are not selected in two separate RS processes for each response. Instead, a conjoint binding selection process might be in place in which response-related codes (i.e.,

spatial codes and modality codes) need to be bound together in accordance with task instructions.

### Unresolved issues

However, even though response compounds in the single-onset paradigm do not appear to involve two distinct response selection processes within each trial, all previous crosstalk studies (including those examining response compounds) have in common that they involve the presence of response selection in the first place, in that each trial involves the selection of the correct responses or response compound among alternatives. Thus, it is still an open issue whether the mere execution of two incompatible responses is sufficient for cross-response crosstalk effects to occur (i.e., due to the mere presence of incongruent active codes), or whether crosstalk effects only arise when incompatible responses need to be selected within a trial (and underlying response codes undergo the process of activation). In fact, a rigorous test of this issue would require to compare performance in a condition involving the selection of one (out of two) response compound alternatives against performance in a condition without such RS demands, that is, a condition in which the same response compound is repeated throughout a block of trials.

A second unresolved issue from previous multiple-action studies is the question of whether dual-response costs can also occur in the absence of any requirements of selecting a response compound and in the absence of response incompatibility (i.e., adverse crosstalk) within the response compound. In this case, it is still possible that general unspecific dual-execution costs (in terms of a general motor execution bottleneck) are at play whenever two responses are executed in temporal proximity. Again, this open issue can only be resolved in an experimental setting requiring the execution of compatible response compounds without any selection requirements. This issue is particularly interesting to study in a situation involving two fairly distinct motor systems with a high a priori probability of separate execution-related processing (here: oculomotor and manual output system, see also Huestegge, Pieczykolan, & Koch, 2014).

### The present study

The aim of the present study is to further specify the underlying mechanisms of cross-response crosstalk. Therefore, we examined if crosstalk within response compounds occurs both in the presence and absence of response alternatives, that is, in the presence or absence of RS. Furthermore, we examined whether there is any indication of general dual-execution costs in the absence of both crosstalk and RS demands. We adapted the setup by

Huestegge and Koch (2009, 2010) by having participants respond to lateralized auditory stimuli to the left or right ear with either a saccade (to the left or right), or a manual key press (operated by the left vs. right index finger), or both. This effector combination is especially suited to study spatial crosstalk effects because both responses are inherently spatial at the fundamental motor level (e.g., unlike vocal utterances such as “left” or “right”). Furthermore, while manual response control is known to be quite sensitive to RS demands (Hick, 1952) in that RTs increase with the number of potential response alternatives, saccades are reported to be much less sensitive in this regard (e.g., Kveraga, Boucher, & Hughes, 2002). Therefore, any dual-response costs for saccades would be informative regarding the susceptibility of saccades to crosstalk from other response modalities (see Huestegge & Koch, 2013; Huestegge et al., 2014, for bidirectional crosstalk between vocal, manual, and oculomotor responses).

Response selection was manipulated by introducing two conditions. In one condition, we minimized RS demands by requiring participants to perform the same response (or response compound) throughout a block of trials (similar to a simple RT task without RS requirements). In the other condition, the specific response (compound) varied randomly from trial to trial (analogous to a two-choice RT task involving RS). *Crosstalk* was manipulated in a standard manner (e.g., Navon & Miller, 1987) by requiring participants to either respond with spatially compatible responses (e.g., combining a left saccade with a left manual response) or with spatially incompatible responses (e.g., combining a left saccade with a right manual response). In line with previous studies, we interpret differences in dual-response costs between compatible and incompatible conditions as evidence for dual-response interference based on crosstalk. In Experiment 1, response–response (R–R) incompatibility was operationalized by combining S–R compatible saccades with S–R incompatible manual responses. Due to the design constraints of utilizing a single stimulus, it is unavoidable to introduce S–R compatibility for one modality only. To assess whether the decision to introduce S–R incompatibility for the manual (instead of oculomotor) responses in Experiment 1 affected the data pattern we ran an additional Experiment 2 that served as a control condition involving the reversed mapping (i.e., S–R incompatible saccades combined with S–R compatible manual responses). This also allowed us to assess the differential impact of S–R mapping conflict on response modalities with different overall prioritization (see Huestegge & Koch, 2013).

Importantly, the present research design—unlike previous studies (e.g., Fagot & Pashler, 1992; Holender, 1980; Huestegge & Koch, 2009, 2010)—included a crucial, novel condition, namely the execution of response compounds

(involving compatible or incompatible responses) without RS demands. Thus, unlike numerous previous studies on crosstalk, we are able to examine the role of cross-response crosstalk in the *absence* of any RS processes: If adverse crosstalk effects only occur when a trial involves response (compound) selection (and thus the process of activating the relevant response codes), then the effects of crosstalk on dual-response costs should be larger in RS presence (vs. absence) conditions suggesting that R–R crosstalk mainly operates on the RS level. This would be in line with previous findings in the area of S–R compatibility effects, which also tend to disappear in the absence of RS demands (Broadbent & Gregory, 1967). This prediction is tested against the null hypothesis that crosstalk effects are similar with and without RS demands (i.e., similar difference in *dual-response costs* between compatible and incompatible responses). Finally, the design also allows us to test the novel hypothesis of whether dual-response costs still occur under conditions without any RS requirements and without adverse effects of crosstalk (i.e., mere dual-execution costs for compatible responses on the response execution stage). Note that the present hypotheses refer to dual-response *costs* (i.e., differences between dual- and single-response performance as an index of dual-response interference) and to potential differences between dual-response costs (e.g., as a function of crosstalk), and not to effects on absolute RT levels (e.g., mere RT increases due to the presence of RS demands would be an obvious and trivial observation).

## Experiment 1

### Method

#### *Participants*

Forty-eight participants with normal or corrected-to-normal vision were randomly assigned to two cross-response compatibility (spatially compatible/incompatible) groups (17 women and 7 men in each group). The mean age was 23 years (SD = 3.7, range = 19–36). They gave informed consent and received course credits or monetary reimbursement for participation.

#### *Stimuli and apparatus*

Participants were seated 65 cm in front of a 20-inch cathode ray tube (temporal resolution: 100 Hz; spatial resolution: 1024 × 768 pixels) with a keyboard in front of them. Saccades were registered using a head-mounted Eyelink II infrared reflection system (SR Research, Osgoode, Ontario, Canada) by measuring the position of the right pupil with a temporal resolution of 500 Hz. We used the SR Research

Experiment Builder software (SR Research, Osgoode, Ontario, Canada) for programming and analyzing purposes. A chin rest was installed to minimize head movements.

A green fixation cross was presented at the center of a black screen. Two green rectangular squares ( $8.3^\circ$  to the left and right of the fixation cross) served as saccade targets and remained present throughout. The size of the fixation cross and the saccade targets was  $1/3^\circ$  each. On the keyboard, two keys (left Ctrl and right arrow) were chosen from the bottom key row as response keys. Participants responded with their left and right index fingers. Thus, unlike in research on eye–hand coordination, the two types of movements (saccades, manual responses) did not share a common target. The imperative auditory stimulus consisted of an easily audible 1000-Hz pure tone (50 ms duration) that was presented to the left or right ear via supra-aural headphones.

### Procedure

In each trial, participants responded to the unilateral (left or right) auditory stimulus. Participants in the *compatible responses group* were instructed to respond by pressing the spatially compatible key (manual response in single-response blocks), by moving their gaze to the spatially compatible square on the screen (saccade response in single-response blocks), or both (dual-response blocks). They were instructed to respond as fast and accurately as possible. The *incompatible responses group* received the same instructions for the saccades, whereas manual responses had to be executed spatially incompatible to the stimulus (e.g., a left tone was mapped to a right key press; see Huestegge & Koch, 2010, for a similar manipulation) to elicit adverse crosstalk effects.

While in *response selection presence* conditions stimuli were presented to the left vs. right ear in a pseudo randomly constructed sequence (i.e., a random sequence that was the same for all participants) yielding blocks with a two-alternative forced choice task, the *response selection absence* conditions involved the presentation of the same stimulus throughout a block of trials (similar to a simple-RT task), resulting in response (compound) repetitions only. Note that the two RS conditions differ with respect to both the number of response demands and the number of stimuli (e.g., it would also be possible to use two stimuli in a go/no-go design to keep the number of stimuli constant). However, we deliberately decided to implement a most basic condition with minimized demands regarding RS. Further note that it cannot be ruled out that a go/no-go design still involves RS, namely between go and no-go responses.

To minimize the potential for anticipatory responses (especially in RS absent conditions), we introduced a variable inter-stimulus interval (1500, 2000, and 2500 ms,

equally distributed). In single-saccade blocks and dual-response blocks, participants were instructed to return their gaze to the central fixation cross after each response. In single-manual blocks, participants were required to remain fixated on the central fixation cross throughout the block.

Participants accomplished 12 blocks of 30 trials presented in four sequences of three blocks each (e.g., single saccade, single manual response, dual response). A calibration routine was administered at the beginning of each block.

### Design

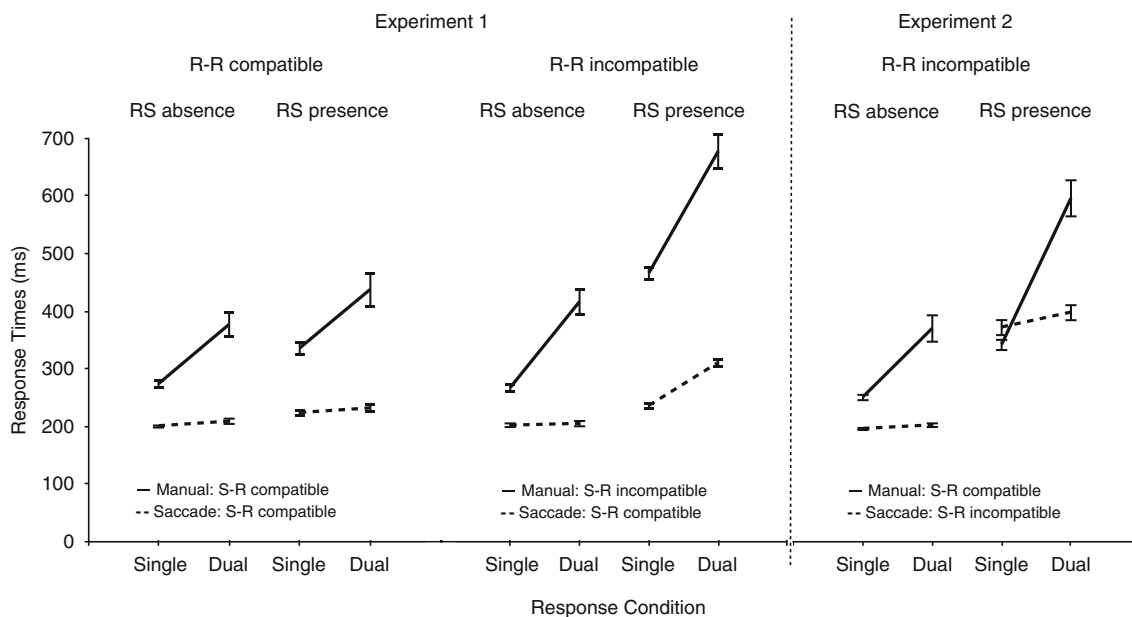
We utilized four independent variables. Response modality (saccade vs. manual), response condition (single response vs. dual response), and RS (presence vs. absence) were manipulated block-wise within participants. Compatibility (compatible vs. incompatible) was manipulated between participants to avoid potential carry-over effects. The order of the three response condition blocks (saccade, manual, dual) and the order of RS conditions (presence, absence) were counterbalanced across participants to prevent potential confusion regarding compatibility instructions. RTs and errors for saccades and manual responses were recorded as dependent variables.

## Results

### Response times

In single-manual blocks, we excluded 4.7% of trials in the compatible group and 6.5% of trials in the incompatible group due to erroneous saccade responses. Figure 1 shows the mean RTs for saccades and manual responses as a function of response modality, response condition, RS, and compatibility. A mixed four-way ANOVA revealed a significant effect of response modality,  $F(1,46) = 315.71$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.87$ , indicating the typical finding that saccades (223 ms) are initiated faster than manual responses (399 ms). The main effect of response condition was significant, too,  $F(1,46) = 102.48$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.69$ , indicating longer RTs in dual-response conditions (351 ms) than in single-response conditions (270 ms), reflecting overall dual-response costs of 81 ms. Furthermore, there was a significant main effect of RS,  $F(1,46) = 200.49$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.81$ , with longer RTs in blocks involving RS (358 ms) than in blocks without RS (264 ms). The group comparison revealed a significant main effect of compatibility (336 ms in the incompatible group vs. 286 ms in the compatible group),  $F(1,46) = 11.24$ ,  $p = 0.002$ ,  $\eta_p^2 = 0.20$ .

More importantly, all two-way interactions were statistically significant. The interaction of RS and response



**Fig. 1** Mean RTs for saccades and manual responses in Experiment 1 and 2 as a function of response condition (single and dual) and RS (RS absence vs. RS presence) for conditions involving (R–R) compatible and incompatible responses. In Experiment 1, response

incompatibility was introduced by utilizing an incompatible S–R mapping for manual responses, while in Experiment 2 the S–R mapping for saccades was incompatible. Error bars represent standard errors

condition,  $F(1,46) = 10.70$ ,  $p = 0.002$ ,  $\eta_p^2 = 0.19$ , indicates that dual-response costs were greater when RS was present (96 ms) than when it was absent (64 ms). The interaction of RS and compatibility,  $F(1,46) = 60.07$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.57$ , indicated a more substantial effect of RS in incompatible conditions (145 ms) than in compatible conditions (42 ms). The interaction of RS and modality,  $F(1,46) = 200.87$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.81$ , indicates a larger impact of RS on manual responses (142 ms) than on saccades (45 ms). The interaction of response condition and compatibility showed that dual-response costs were almost twice as high when responses were incompatible vs. compatible (106 vs. 55 ms),  $F(1,46) = 10.04$ ,  $p = 0.003$ ,  $\eta_p^2 = 0.18$ , while the interaction of response condition and modality indicates that dual-response costs were substantially greater for manual responses (139 ms) than for saccades (23 ms),  $F(1,46) = 60.36$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.57$ . The interaction of compatibility and modality,  $F(1,46) = 12.95$ ,  $p = 0.001$ ,  $\eta_p^2 = 0.22$ , indicates a smaller compatibility effect for saccades (13 ms) than for manual responses (85 ms).

Importantly, the three-way interaction of response condition, RS, and compatibility was significant,  $F(1,46) = 10.64$ ,  $p = 0.002$ ,  $\eta_p^2 = 0.19$ , revealing that dual-response costs were smaller when RS was absent (74 ms) than when it was present (138 ms) in the incompatible group, but they were virtually the same (55 vs. 55 ms) in the compatible group. This result demonstrates that RS mainly affects dual-response costs when spatial

conflict needs to be resolved, or, conversely, that crosstalk affects dual-response costs mainly in the presence of RS demands. The interaction of RS, compatibility, and modality was significant, too,  $F(1,46) = 72.14$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.61$ , but neither the interaction of modality, response condition, and compatibility,  $F(1,46) = 2.02$ ,  $p > 0.15$ , nor the interaction of modality, response condition, and RS,  $F < 1$ , were significant. Thus, there was no statistical evidence for differences in dual-response costs between modalities dependent on the specific R–R compatibility or RS demands. Finally, there was no significant four-way interaction,  $F < 1$ , indicating that the important three-way interaction of response condition, RS, and compatibility did not significantly differ between (S–R incompatible) manual responses and (S–R compatible) saccades.

Post hoc analyses of dual-response costs for each modality in all experimental conditions (i.e., for each line in Fig. 1) showed that saccades exhibited significant dual-response costs only in RS blocks (72 ms in the incompatible responses group,  $t(23) = 8.3$ ,  $p < 0.001$ ; 8 ms in the compatible group,  $t(23) = 2.5$ ,  $p = 0.021$ ), but not in blocks without RS requirements ( $< 8$  ms, all  $ps > 0.15$ ). In contrast, manual dual-response costs were significant throughout all conditions, all  $ps < 0.05$ , including the condition involving compatible responses without RS requirements. Interestingly, a post hoc analysis of manual RTs in conditions without RS revealed no significant interaction between compatibility and response condition,  $F(1,46) = 1.88$ ,  $p > 0.10$ , whereas the same analysis for

conditions involving RS resulted in a significant interaction,  $F(1,46) = 7.08$ ,  $p = 0.011$ ,  $\eta_p^2 = 0.13$ .

Error rates (overall mean = 2.2%) were deemed too low to conduct meaningful statistical analyses. There was no numerical trend in the data that indicated a speed–accuracy trade-off.

## Discussion

We observed dual-response costs for manual responses in all experimental conditions, even in the compatible group without RS requirements. This finding suggests that the execution of multiple responses per se leads to *general dual-execution costs*, that is, costs that occur in the absence of both RS and adverse crosstalk. This novel finding demonstrates that a substantial portion of dual-response costs that were previously reported in research on cross-modal action control (e.g., Huestegge & Koch, 2009, 2013) occurs due to such unspecific response coordination costs at a late processing stage related to response execution. The fact that the effect of RS on dual-response costs was greater for manual than for oculomotor responses could be interpreted in line with previous observations that saccades are less sensitive to RS manipulations (Kveraga, Boucher, & Hughes, 2002; Pieczykolan & Huestegge, 2017) than manual responses (e.g., Hick, 1952).

Beside these general dual-execution costs, our results clearly suggest a strong effect of cross-response crosstalk within a trial (Navon & Miller, 1987) as reflected in worse performance in spatially incompatible (compared to compatible) conditions. This finding is in line with previous research on simultaneously executed saccades and manual responses (Huestegge & Koch, 2009). Most importantly, however, the presence of a significant three-way interaction of response condition, compatibility, and RS demonstrated that crosstalk affects dual-response costs mainly when RS demands are present in the first place. Thus, the mere presence of two conflicting active response codes (in RS absent trials, where these codes are likely pre-activated prior to the beginning of each trial) is not sufficient to yield adverse crosstalk effects. Instead, adverse effects of crosstalk appear to occur during the process of *activating* conflicting response codes within a trial.

As already noted in the introduction, Fagot and Pashler (1992) convincingly demonstrated that triggering two responses with a single aspect of a common stimulus (as was the case in the present experiment) involves only one unitary (but complex) RS process for the response compound (similar to a single task). Subsequent research has indicated that this is also the case when the two responses are spatially incompatible (Huestegge & Koch, 2010, see introduction). This previous work effectively rules out an

interpretation of two separate RS in each trial in terms of classic dual-task frameworks, for example, within the traditional RS bottleneck account (Pashler, 1994). Instead, the present findings are rather suggesting that the presence of RS in conjunction with adverse crosstalk conditions increased the difficulty of a unitary (but complex) selection process that comprises both responses (e.g., see the framework by Huestegge & Koch, 2010). The particularly large manual dual-response costs in this condition might be due to general effector-based processing prioritization assigned to oculomotor (vs. manual) control demands (see Huestegge & Koch, 2013).

Since the spatial incompatibility between responses was introduced through a spatially incompatible S–R mapping for manual responses, one might argue that the important three-way interaction described above may have been caused by the introduction of S–R (instead of or in addition to R–R) incompatibility. Previous research utilizing the same single-stimulus paradigm (Huestegge & Koch, 2009), however, suggested that the simultaneous introduction of S–R incompatibility for manual and saccade responses (resulting in R–R compatibility despite an even greater “amount” of overall S–R incompatibility) substantially *reduced* dual-response costs (when compared to a mixed S–R compatibility condition as our crosstalk present condition). Nevertheless, to rule out that the decision to introduce S–R incompatibility for manual responses in Experiment 1 was a driving force behind the observed data pattern, we conducted Experiment 2 in which we collected data in an alternative condition with compatible S–R mappings for manual responses and incompatible S–R mappings for saccades. Apart from these replication purposes, Experiment 2 also helps us to assess the differential impact of S–R mapping conflict on output systems with different overall prioritization (see Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014).

## Experiment 2

### Method

#### *Participants*

A new group of 24 students (16 woman and 8 men) participated in Experiment 2 with a mean age of 23 years ( $SD = 2.1$ , range = 20–30).

#### *Apparatus, stimuli, procedure, and design*

Apparatus and stimuli were the same as in Experiment 1. The overall procedure was also the same except for the instruction to respond with S–R incompatible saccades and

S–R compatible manual responses. Regarding the design, it is important to note that we tested only one (*incompatible responses*) group of participants to compare the results with those from the corresponding “incompatible responses” group of Experiment 1.

## Results and discussion

To ensure that our main conclusions from Experiment 1 did not depend on the particular S–R mapping implementation, we analyzed the data of the incompatible responses group of Experiment 2 by directly comparing them to the incompatible responses group from Experiment 1. We thus applied a mixed four-way ANOVA with the independent variables response modality, response condition, RS, and S–R mapping (1: S–R incompatible manual responses and S–R compatible saccades, 2: S–R compatible manual responses and S–R incompatible saccades). If the specific S–R mapping implementation mattered, this would become apparent in any interaction involving S–R mapping and response condition suggesting an impact of the S–R mapping on dual-response interference.

### Response times

We excluded 1.6% of the data due to anticipatory responses (< 150 ms for manual responses and < 70 ms for saccades) and due to erroneous saccades in manual-single trials. As in Experiment 1, there were significant main effects (see Fig. 1) of modality,  $F(1,46) = 242.37$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.84$ , response condition,  $F(1,46) = 109.05$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.70$ , and RS,  $F(1,46) = 271.26$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.86$ . However, mean RTs did not significantly differ between the two S–R mapping groups across experiments (336 ms vs. 330 ms),  $F < 1$ .

Modality and S–R mapping interacted significantly,  $F(1,46) = 35.54$ ,  $p = 0.001$ ,  $\eta_p^2 = 0.44$ , indicating that the typical compatibility effect (i.e., S–R compatible responses are faster than incompatible responses) resulted in a trade-off across modalities: S–R incompatible manual RTs were 64 ms slower than compatible ones while S–R compatible saccades were 54 ms faster than incompatible saccades. As in Experiment 1, the interaction of RS and modality,  $F(1,46) = 58.99$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.56$ , indicates a larger impact of RS on manual responses (187 ms) than on saccades (124 ms), and the interaction of RS and response condition,  $F(1,46) = 35.84$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.44$ , indicates larger dual-response costs when RS was present (136 ms) compared to absent (67 ms). The interaction of response condition and modality indicates greater dual-

response costs for manual responses (177 ms) than for saccades (26 ms),  $F(1,46) = 67.25$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.60$ . There was no significant interaction of RS and S–R mapping,  $F = 1.24$ ,  $p = 0.27$ , suggesting that S–R mapping had no significant influence on the impact of RS, nor an interaction of response condition and S–R mapping,  $F < 1$ ,  $p = 0.68$ , suggesting no significant influence of S–R mapping on dual-response costs (thus replicating results from our previous studies utilizing the same crossed compatibility manipulation in a different theoretical context, Huestegge & Koch, 2010; Pieczykolan & Huestegge, 2014).

Importantly, the three-way interaction of response condition, RS, and S–R mapping was not significant either,  $F < 1$ , suggesting that RS affected dual-response costs in a comparable way regardless of the particular S–R mapping across experiments. Also, the interaction of response condition, modality, and S–R mapping was not significant,  $F < 1$ ; thus, there was no statistical evidence for a difference in dual-response costs between modalities dependent on S–R mapping. Interestingly, there was a significant interaction of modality, RS, and S–R mapping,  $F(1,46) = 121.79$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.73$ , showing that the effect of RS was larger on S–R incompatible manual responses than on S–R compatible saccades (222 vs. 68 ms) in Experiment 1 while it was larger on S–R incompatible saccades than on S–R compatible manual responses in Experiment 2 (180 vs. 153 ms). This result supports our previous observation that RS and crosstalk (here: between the stimulus and each individual response) are interdependent, because the effect of RS was larger on the respective S–R incompatible response. Additionally, the interaction between modality, response condition and RS was significant,  $F(1,46) = 8.53$ ,  $p = 0.005$ ,  $\eta_p^2 = 0.16$ , indicating that the impact of response condition on dual-response costs was larger for manual responses than for saccades. Note that these results do not contradict any conclusion drawn in Experiment 1, because they do not indicate any influence S–R mapping on the relevant interaction of RS and dual-response costs.

Finally, there was a significant four-way interaction of modality, response condition, RS, and S–R mapping,  $F = 11.81$ ,  $p = 0.001$ ,  $\eta_p^2 = 0.20$ , revealing that the previously reported non-significant three-way interaction between response condition, RS, and S–R mapping was the result of averaging across modalities. Separate post hoc three-way ANOVAs for manual responses and saccades revealed a non-significant three-way interaction for manual responses, i.e., dual-response costs of S–R compatible manual responses in Experiment 2 were increased in a comparable way by the presence of RS as were S–R incompatible manual responses in Experiment 1,  $F(1,46) = 3.47$ ,  $p = 0.069$ . For saccades, however, the



respective three-way interaction was significant,  $F(1,46) = 8.36$ ,  $p = 0.006$ ,  $\eta_p^2 = 0.15$ , suggesting that the presence of RS caused larger dual-response costs for S–R compatible saccades in Experiment 1 than for S–R incompatible saccades in Experiment 2, while there were no dual-response costs in RS absent conditions. One-sided  $t$  tests comparing single- and dual-response RT for (S–R incompatible) saccades in the RS present condition revealed significant dual-response costs of 25 ms (cf., 72 ms for S–R compatible saccades in Experiment 1),  $t(23) = 2.03$ ,  $p = 0.027$ , but no significant dual-response costs without RS,  $p = 0.19$ , hence replicating the data pattern from Experiment 1.<sup>1</sup>

Taken together, the important conclusion drawn in Experiment 1, namely that RS presence is a necessary precondition for observing strong crosstalk effects on dual-response costs, is not dependent on the specific S–R mapping implementation. In particular, the choice of S–R incompatible saccades and S–R compatible manual responses results in reduced interference for saccades, which is compensated for by an increase of interference for manual responses. This is in line with previous observations of flexible resource scheduling in cross-modal dual-response control, where incompatible S–R mappings were shown to be prioritized over compatible S–R mappings (Pieczykolan & Huestegge, 2014). In sum, the data from Experiment 2 support the conclusions from Experiment 1.

## General discussion

The present study was aimed at examining the interplay of different mechanisms underlying multiple response control by investigating two well-known sources of interference—crosstalk and RS—in cross-modal response compounds. Specifically, we aimed at the questions of whether a) response-based crosstalk effects and b) general dual-execution costs for compatible responses require the presence (vs. absence) of RS demands. Participants responded to auditory stimuli by performing single responses and dual-response compounds in two response modalities (saccades and manual responses). We manipulated RS and crosstalk independently. RS was manipulated by comparing performance in blocks with either repeating or switching

response alternatives (addressing the presence/absence of RS). Crosstalk was manipulated by comparing conditions involving the simultaneous execution of spatially compatible or incompatible responses (addressing crosstalk). Previous research and theory on cross-response crosstalk effects in multiple-response control did not focus on the role of RS in terms of a presence or absence of a choice among response alternatives. Instead the focus was mainly on examining cross-response crosstalk between two independent tasks (e.g., Logan & Gordon, 2001; Meyer & Kieras, 1997; Navon & Miller, 1987, 2002). Thus, these previous studies were not suited to address the present research questions, which require an analysis of response compounds by utilizing a single-onset paradigm (Holender, 1980; Fagot & Pashler, 1992) with the simultaneous manipulation of both crosstalk and RS demands.

The experiments yielded two important novel findings: First, response-based crosstalk effects (i.e., larger dual-response costs for incompatible vs. compatible responses) require the presence of response selection demands (i.e., the corresponding process of activating response codes within a trial). Second, general dual-execution costs can still be observed in the absence of both response selection requirements and response incompatibility. These findings indicate that crosstalk operates on the level of response selection in form of interference between response codes during their activation. However, general dual-execution costs occur on the execution-related processing level, even for quite distinct output systems such as manual and saccade control systems. The interaction between crosstalk and response selection indicates that the mere execution of incompatible (vs. compatible) responses does not per se negatively affect dual-response control—a finding that is independent of the particular assignment of S–R (in)compatibility to one of the two response modalities (as evidenced by similar results in Experiments 1 and 2).

Interestingly, our interpretation that crosstalk occurs during response code activation (and not between already pre-activated response codes) is in line with previous suggestions for the localization of crosstalk in the processing chain (Hommel, 1998; Lien & Proctor, 2002; Schubert et al., 2008). Specifically, these authors suggested two sub-stages related to response processing. First, a fast, parallel response activation stage (that is automatically prompted by stimulus processing) is assumed during which crosstalk is supposed to occur. Secondly, a subsequent process of selecting the correct response occurs (sometimes referred to as response identification, see Schubert et al., 2008), which is a slower process that is subject to serial processing in dual-task control. Thus, the prediction that crosstalk is assumed to take place during the activation of response codes is clearly corroborated by our present findings. However, our findings also go beyond these

<sup>1</sup> We decided to report here the direct comparison of the incompatible conditions from both experiments. Additionally, we computed an analysis including the R–R incompatible condition of Experiment 2 with the R–R compatible condition of Experiment 1 (analogous to Experiment 1 analyses). The results do not contradict the findings in Experiment 1. Importantly, our main finding in Experiment 1, namely the interaction of response condition, RS, and R–R compatibility, was replicated showing that crosstalk has a larger impact on dual-response interference under increased RS demands and therefore operates rather on the level of RS than on the level of response execution.

previous studies in that they suggest that this localization of crosstalk effects also holds in the context of cross-modal response compound control.

It is important to note that our present manipulation of RS may not have selectively affected the presence/absence of the RS stage only. Instead, it has been suggested that such a manipulation could also affect, for example, preparatory states at stimulus onset (e.g., Danek & Mordkoff, 2011). However, our conclusions do not rely on the assumption of manipulating only selection per se. Instead, it was important to find a condition with minimized RS demands, and the repetition of the same demands across a block of trials is probably the most efficient measure to achieve this goal. Nevertheless, a clear prediction of the present study is that similar results regarding the localization of crosstalk effects in response compound control also emerge when utilizing a go-/no-go-setup as an alternative to the present RS conditions.

The experiments also revealed several replications of prior observations: For example, the data from Experiment 1 replicated many previous reports (starting with Donders, 1869) of a substantial impact of the presence of RS on response control in that the presence of selection requirements caused elevated RTs throughout all (single- and dual-response) conditions, also in the absence of crosstalk. Furthermore, and in line with previous studies, we found evidence for general adverse crosstalk based on response code conflict. Interestingly, and resembling previous observations (Huestegge & Koch, 2009, 2010), response incompatibility also affected the first (here: oculomotor) response in addition to the second (here: manual) response. This suggests bidirectional crosstalk similar to related findings in the context of dual-task setups (e.g., Ellenbogen & Meiran, 2010; Hommel & Eglau, 2002; Koch & Prinz, 2002; Lien & Proctor, 2000, 2002; Logan & Gordon, 2001; Logan & Schulkind, 2000; Miller, 2006; Miller & Alderton, 2006), which is usually interpreted in terms of interference during the parallel activation of response features (Hommel, 1998; Schubert et al., 2008).

Our observation of general, unspecific dual-execution costs resembles the previously suggested, but rather unspecific notion of concurrence costs (e.g., Berlyne, 1957; Herman & Kantowitz, 1970; Logan & Gordon, 2001; Navon & Gopher, 1979). The fact that dual-response costs were especially pronounced for manual responses, however, is at odds with previous observations showing largely unaffected manual responses in the context of additional vocal demands in the single-onset paradigm (Fagot & Pashler, 1992; Holender, 1980). Thus, the present findings suggest that the specific pattern of dual-response costs is not fixed for each effector system, but rather depends on the specific combination of effector systems, probably due

to effector system prioritization (Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014).

As mentioned earlier, previous studies on multiple-action control usually did not include a condition in which a pre-selected response (compound) was repeatedly executed (i.e., without any RS requirements). A notable exception are few studies involving two manual tasks that also reported evidence for dual-response costs in the absence of RS requirements (Karlin & Kestenbaum, 1968; Reynolds, 1966; Schubert, 1999). However, it is important to note that these studies utilized distinct, temporally separated stimuli (one for each response) instead of a common stimulus, so it is difficult to ascribe the observed costs solely to the coordination of dual-response execution. Specifically, while in a sequential-stimulus paradigm the prolongation of RT2 could be attributed to temporal uncertainty about the occurrence of the second stimulus (see Pashler, 1994), the costs within the present single stimulus paradigm cannot be explained by such a temporal uncertainty account. Thus, the present results represent first unequivocal evidence for general dual-execution costs in cross-modal response control (see Garry & Franks, 2000, for similar observations in the field of intra-modal, bimanual motor coordination). Note that these cross-modal dual-response costs are also reminiscent of intra-modal effects of response complexity (e.g., double-press responses vs. single-press responses) on RTs, suggesting similar underlying mechanisms related to motor programming complexity (e.g., Christina, Fischman, Vercruyssen, & Anson, 1982).

We would like to point out that the present analyses (in the context of response compound control) also have important implications for dual-task theories, since they further pinpoint the underlying cross-response interference mechanisms that should also be relevant for dual-task control. Specifically, our results demonstrate that some interference mechanisms, which are postulated to explain dual-task interference, do not necessarily depend on features of typical dual-task settings but are of a more basic nature: For example, response-based crosstalk does not require two distinct task processing streams within a trial. Instead, any two responses can still interfere on a general, execution-related level even in the absence of any response selection demands or response incompatibility. Especially the latter finding may indicate that in many previous dual-task studies the contribution of specific interference (e.g., based on within-trial conflict resolution or on response selection requirements) might have been smaller than previously believed.

Finally, the present results have several additional implications for current theorizing on multiple-action control. First, they demonstrate that models such as EPIC (Meyer & Kieras, 1997) should consider not only oculomotor control as a mere prerequisite of visual perception,

but also rather as a motor control unit in its own right, and thus exhibiting similar basic phenomena (regarding its interaction with other motor units) as do the more established manual and vocal processor units. Second, the present results are also informative regarding other frameworks that have not explicitly considered oculomotor interference (e.g., Logan & Gordon, 2001; Navon & Miller, 2002; Tombu & Jolicœur, 2003). Our present results demonstrate that oculomotor control demands can strongly interfere with other output-related control systems and that this interference is not only determined by the relation between response codes (i.e., crosstalk). Instead, it also occurs on the more general level of mere execution-related processing, that is, regardless of response content and even for rather “dissimilar” output domains.

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