

Dual-Task Crosstalk Between Saccades and Manual Responses

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Between-task crosstalk has been discussed as an important source for dual-task costs. In this study, the authors examine concurrently performed saccades and manual responses as a means of studying the role of response-code conflict between 2 tasks. In Experiment 1, participants responded to an imperative auditory stimulus with a left or a right key press (manual task), a left or a right saccade (saccade task), or both. In Experiments 2 and 3, participants crossed their hands, and a modest (Experiment 2) or substantial (Experiment 3) degree of between-task response-code conflict through specific instructions was introduced. In Experiment 4, response codes across tasks were compatible, and stimulus–response mappings in both tasks were incompatible. Overall, the results indicate that performance not only in manual responses but also in saccades suffers from dual-task conditions, even though saccades were typically performed first and are usually assumed to be controlled quite independently. Moreover, the systematic introduction of response-code conflict between tasks modulated the pattern of dual-task performance. The authors propose confusability of response codes as an underlying mechanism of the observed effects of between-task crosstalk.

Keywords: dual-task interference, crosstalk, saccade, eye movement, response code, compatibility

It is a well known fact that it is more difficult to execute two tasks at a time than a single task alone (Solomon & Stein, 1896). Dual-task settings lead to more errors, longer response times (RTs), or both; these effects are typically referred to as dual-task costs. On the basis of such findings, two major sources for these costs have been discussed, namely, limited capacity and crosstalk.

Limited-capacity accounts state mainly that dual-task costs arise because both tasks compete for the same limited resources or processing mechanisms. Two prominent theories are based on this assumption. The *response selection bottleneck model* (Pashler, 1994) assumes that performance on each task can be described as a series of processing stages, ranging from perceptual processing to response execution. Empirical evidence suggests that although some stages can be processed in parallel for both tasks, a central response selection stage is only dedicated to one task at a time, thus constituting a bottleneck (e.g., Pashler, 1994). Each time one task is involved in response selection processes, response selection in a second task cannot start until this process is finished in the first. By comparison, the *strategic response deferment model* (Meyer & Kieras, 1997) assumes that even at central stages, information can be processed in parallel. However, because of the limitation of central resources, a strategic allocation is necessary, yielding dual-task costs in either one or both tasks (see also Logan

& Gordon, 2001; Navon & Miller, 2002; Tombu & Jolicoeur, 2003).

A theoretically distinct source of dual-task costs is crosstalk. On a general level, the term *crosstalk* refers to any influence of information processing between communication channels. More specifically, between-task crosstalk refers to any influence between two tasks that share physical features or involve associated conceptual dimensions, such as overlapping stimulus and/or response features or dimensions (Navon & Miller, 1987). For example, when both tasks require “left” versus “right” decisions, they are prone to mutual influence, probably resulting from response-code confusion.

However, as far as response codes in both tasks are fully compatible, for example, when both require a left decision, response-code confusion should be harmless. However, overlapping response codes bearing potentially conflicting information should severely hamper dual-task performance, leading to outcome conflict or, more specifically, cross-task response conflict (Navon, 1985; Navon & Miller, 1987).

Previous studies on between-task crosstalk on the level of response codes have mainly focused on specific crosstalk effects, for example, by comparing performance on trials with incompatible and compatible response codes within the same experiment (e.g., Lien & Proctor, 2000). However, these specific comparisons presuppose crosstalk on a more general level that is already introduced by implementing two tasks with response-code overlap. Even compatible trials might already suffer from crosstalk, because of the fixed presence of overlapping response codes. The comparison of RTs between compatible and incompatible trials therefore likely underestimates the overall amount of crosstalk (see also Koch, in press).

In the present study, we aim at a better understanding of the mechanisms behind crosstalk on a more general level by systematically manipulating the amount of conflict between response

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We thank Elena Zettelmeyer and Philipp Junghans for the collection of the data and those who kindly volunteered to participate in the study. We also thank Glyn Humphreys and Hermann Müller for comments on earlier drafts of this article.

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codes of two tasks. Because we were mainly interested in crosstalk between simultaneous responses, we did not consider experimental paradigms that either explicitly or implicitly suggest seriality in response planning (Meyer & Kieras, 1997), like task switching (Allport, Styles, & Hsieh, 1994; Rogers & Monsell, 1995) or the psychological refractory period (PRP) paradigm (Welford, 1952). Instead, we chose a dual-task setting where two responses are triggered at about the same time (Fagot & Pashler, 1992). By using only one stimulus for both tasks, we gain maximal control over stimulus-related processes.

As a touchstone for the study of crosstalk mechanisms, we chose two response modalities that (in terms of dual-task costs) were previously assumed to be unrelated to a comparatively large extent, namely, saccades and manual responses. For example, studies of eye–hand coordination in the context of reaching, pointing, or grasping, in which participants direct a saccade and a manual response to one common object, did not show consistent evidence for dual-task costs (e.g., Bekkering, Adam, Kingma, Huson, & Whiting, 1994; Hodgson, Müller, & O’Leary, 1999; Lünenburger, Kutz, & Hoffmann, 2000; Mather & Fisk, 1985).

Only a few studies were conducted with the aim to study simultaneously executed saccades and manual responses on a more general level, without involving a common target object for both movements. In an important attempt to tackle this need, Pashler, Carrier, and Hoffman (1993) conducted a series of experiments using the PRP paradigm, in which a manipulation of stimulus onset asynchrony (SOA) for both tasks induces a systematic variation of task overlap. In their study, one task requested a saccade to a visual stimulus, whereas the other task was to respond with a key press to the pitch of an auditory stimulus. The visual stimulus was either presented shortly after (positive SOA) or before the auditory stimulus (negative SOA), but never at the same time. Whereas in many other task combinations more temporal overlap (i.e., shorter SOA) typically leads to a prolongation of RTs in the second task (i.e., the PRP effect; see Pashler, 1994, for a review), the overall data pattern of this study did not consistently provide evidence for such an effect. Pashler et al. (1993) explained these results by assuming that saccades and manual responses can be executed without much competition for central limited resources.

However, two main issues pose a challenge for a conclusive interpretation of these data in the context of the present study. First, two different stimulus–response (S-R) modality pairings were used in the experiments. Manual movements were triggered by auditory stimuli, whereas saccades were triggered by visual input. Recent research suggests that some S-R modality pairings may lead to performance advantages, such as the execution of manual responses to visual stimuli or the production of speech output in response to auditory stimuli, compared with the opposite pairings, respectively (Hazeltine, Ruthruff, & Remington, 2006; Levy & Pashler, 2001; McLeod & Posner, 1984; Ruthruff, Hazeltine, & Remington, 2005; Stelzel, Schumacher, Schubert, & D’Esposito, 2006). In line with this research, one might argue that in responding with a saccade to a visual stimulus the same sensorimotor system is involved, which should therefore be an especially advantageous S-R modality pairing. Such differences in the relative ease of modality pairings make any interaction of saccades and manual responses in PRP designs difficult to interpret.

Second, Pashler et al. (1993) studied dual-task effects by implementing PRP methodology. However, saccades were so fast

that even in conditions in which the stimulus for the saccade task was presented a relatively long time after the presentation of the stimulus of the manual task, the saccade response was often given before the manual response. As a consequence, a basic prerequisite to a successful interpretation of PRP results is likely to be violated, namely, that the sequence of responses should at least in the majority of cases be in accordance with the sequence of the presentation of the stimuli. Together with the assumption that the PRP paradigm generally suggests seriality in the processing of the tasks (Meyer & Kieras, 1997), these limitations make it difficult to determine in what way simultaneous saccades and manual responses interact.

Apart from the study of Pashler et al. (1993), Bekkering et al. (1994) and Hodgson et al. (1999) combined saccades and manual responses using dual-task methodology, without consistently finding dual-task costs. However, on the one hand, this might have to do with a lack of statistical power, because, for example, in Bekkering et al. the manual RTs showed a tendency of dual-task costs of about 15 ms with 12 participants. On the other hand, both studies used visual stimuli to trigger both responses, again leading to unbalanced S-R pairings for both tasks. These heterogeneous demands might have concealed dual-task costs.

Taking into account the limitations of the previous studies referred to above, in the present series of experiments, we chose to study the interaction of saccades and manual responses using classic dual-task methodology with a common imperative auditory stimulus for both tasks (equivalent to an SOA of 0 ms). This avoids unbalanced S-R modality pairing effects as well as the difficulties resulting from a PRP design referred to above. Furthermore, both responses are not spatially directed to the same object. This process allows us to study the interaction of saccades and manual responses on a more general level compared with the special case of pointing, in which the common object might lead to coupling effects, as suggested by Bekkering et al. (1994). Instead of pointing, we therefore used key presses as manual responses.

In Experiment 1 of the present study, the auditory imperative stimulus was presented to either the left or the right ear. We asked participants to perform a spatially corresponding saccade, a key press, or both. Significant differences between single-task and dual-task RTs for each effector can be interpreted in terms of dual-task costs. Note that in the dual-task condition, both responses were always compatible (e.g., a leftward saccade was always performed together with a left key press), and therefore no response-code conflict was introduced.

Experiments 2 and 3 addressed the issue of whether performance suffers from a systematically manipulated degree of response-code conflict between the saccade and the manual response. We introduced this conflict by using crossed-hands conditions with different instructions for the manual task while keeping the saccade task the same as in Experiment 1.

In Experiment 2, participants had to cross their hands and were instructed to press the key that corresponds to the direction of the tone, leading to stimulus–effector incompatibility in the manual task, whereas S-R key compatibility was maintained. In the dual-task condition, this manipulation leads to a spatial incompatibility between the effector in the manual task and the saccade direction in the saccade task. Because previous research showed that responses are primarily coded spatially and effector coding plays only a comparatively minor role (e.g., Simon, Hinrichs, & Craft, 1970; Wallace, 1971; see Proctor & Vu, 2006, for a review), it was

likely that we introduced a relatively modest amount of between-task response-code conflict in Experiment 2. Note that the only difference from Experiment 1 was the crossing of the hands, whereas the instruction remained the same.

In Experiment 3, participants also had to cross their hands but were instructed to press the key with the hand that corresponds to the direction of the tone, leading to S-R location incompatibility in the manual task. In the dual-task condition, this manipulation leads to a spatial incompatibility between the response location in the manual task and the saccade direction in the saccade task. By comparison, this instruction should establish relatively more response-code conflict, with a severe effect on dual-task performance.

In Experiment 4, we asked participants to perform saccades and manual responses that were both spatially incompatible to the auditory stimulus, resulting in spatially compatible response codes across tasks. If it is the manipulation of compatibility per se that increased dual-task costs in Experiment 3, then dual-task costs should be even further increased in Experiment 4 because both S-R mappings were incompatible. However, if response-code conflict plays the crucial role in dual-task performance, then there should be decreased dual-task costs in Experiment 4 as compared with Experiment 3.

Experiment 1

Method

Participants. Twelve students from RWTH Aachen university with normal or corrected-to-normal vision took part in this study (10 women and 2 men). Mean age was 25 years ($SD = 7.18$), ranging from 20 to 47. Eleven of the 12 participants were right-handed. They gave their informed consent and received credits for participation.

Apparatus and stimuli. The participants were seated 67 cm in front of a 21-in. cathode ray monitor (temporal resolution: 100 Hz; spatial resolution: $1,240 \times 1,068$ pixels) with a keyboard in front of them. The spacebar of the keyboard was used during calibration routines. Saccade latencies and amplitudes were registered using a head-mounted Eyelink II infrared reflection system (SR Research, Osgoode, Ontario, Canada). An eye camera measured the position of the pupil of the right eye with a temporal resolution of 500 Hz and a spatial resolution of less than 0.022° . A chin rest was used to minimize head movements. Smaller movements of the head were compensated for online with the help of a second camera recording the position of the head relative to the monitor.

A green fixation cross in the middle of the screen as well as two green rectangular squares at 6° to the left and right of the fixation cross remained present throughout. The size of the fixation cross and the rectangular saccade targets was $1/3^\circ$ each. On the keyboard, two keys with a distance of 30 cm (corresponding to a visual angle of 12°) were chosen from the bottom key row as response keys. Participants were asked to respond with their left and right index fingers. Throughout the experiment, they wore headphones for the presentation of the imperative auditory stimuli. The stimuli consisted of a 1000-Hz sine wave presented for 50 ms to either the left or right ear with an intensity that was easily audible.

Procedure. Each trial began with the presentation of the imperative auditory stimulus (50 ms) to either the left or the right ear.

Participants were instructed to respond as fast and accurately as possible by (a) moving their gaze to the spatially compatible square on the screen (saccade task in single-task blocks), (b) pressing the spatially compatible key on the keyboard (manual task in single-task blocks), or (c) doing both (dual-task blocks).

In the two conditions that require saccades (saccade task in single- and dual-task blocks), participants were instructed to return to the central fixation cross after response. Each participant completed nine blocks consisting of 30 trials each. Within each block, stimuli to the left and right were presented in a randomized sequence with an interstimulus interval of 3,000 ms. Prior to each experimental block, participants underwent a calibration routine. Prior to the experiment, participants performed 30 practice trials that were not further analyzed.

Design. The variables of modality (saccade vs. manual response) and task condition (single vs. dual) were manipulated intraindividually and blockwise. For example, 1 participant performed three identical sequences of three blocks in the order saccade response (single task), dual task, and manual response (single task). The order of conditions within each sequence was counterbalanced across participants. The dependent variables were saccade latencies and amplitudes as well as manual RTs and errors.

Results and Discussion

Because of blinks or measurement error, we discarded 2.86% of trials of the saccade task in single blocks and 3.73% of trials in the dual-task condition. In the manual task in single blocks, 1.39% of trials with erroneously executed simultaneous saccades were excluded.

Table 1 shows the mean RTs of saccades and manual responses in single- and dual-task conditions. An analysis of variance (ANOVA) yielded a significant main effect for task condition (single vs. dual), $F(1, 11) = 14.97, p = .003, \eta_p^2 = .58$, indicating longer RTs in the dual-task condition than in the single-task condition. The main effect of modality (saccade vs. manual response) was also significant, $F(1, 11) = 163.68, p < .001, \eta_p^2 = .94$. RTs for saccades were generally shorter than RTs for manual responses (205 ms vs. 368 ms). Note that the interaction of modality and task condition was significant, $F(1, 11) = 17.17, p = .002, \eta_p^2 = .61$. Dual-task costs were more pronounced in manual responses as compared with saccades (58 ms vs. 12 ms). Separate paired t tests (one-tailed) revealed that RTs of manual responses were significantly longer in the dual-task condition than in the single-task condition, $t(11) = 4.44, p < .001$, whereas for the saccades, this effect only approached significance, $t(11) = 1.57, p = .073$. Saccade amplitudes did not differ as a function of task condition, $t(11) = 0.08, p = .938$.

Errors in manual responses occurred only in dual-task conditions ($M = 2.6\%$, $SD = 1.7\%$). Directional errors of saccades did not occur in any condition. The saccade was initiated earlier than the manual response in 96.0% of the dual-task trials, whereas the remainder consisted of reversals from this sequence. However, eliminating these reversals in the analysis did not change the pattern of results.

In summary, the comparison of single-task and dual-task RTs for both effectors clearly suggests that the manual responses are delayed when a simultaneous saccade must be executed. This finding is consistent with previous results from Hodgson et al.

Table 1
Mean Response Times (in Milliseconds) and Standard Errors for the Saccades and Manual Responses in Single-Task Conditions and Dual-Task Conditions for All Experiments

Experiment	Saccade task					Manual task				
	Single task		Dual task		Costs	Single task		Dual task		Costs
	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>		<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	
1	199	7.29	211	9.39	12 [†]	339	13.08	397	20.18	58*
2	198	10.40	219	13.48	21*	419	19.18	473	22.81	54*
3	246	15.06	384	31.23	138*	631	54.27	886	69.63	255*
4	270	22.27	296	27.62	26*	494	29.27	628	40.42	134*

[†] $p < .10$. * $p < .05$.

(1999). Additionally, for the saccade RTs, there was a tendency of a slowing of about 12 ms, but this dual-task effect was not significant.

Experiment 2

In Experiments 2 and 3, we introduced changes in the manual task. If the saccades are generally performed independently of the manual responses, then an introduction of a more difficult manual task should lead neither to an overall increase of the RTs of the saccades nor to a significant increase of dual-task costs for the saccades.

In Experiment 2, we used the same dual-task design as in Experiment 1, but the manual task was changed in one important respect. Participants had to cross their hands, holding their left index finger above the right key and their right index finger above the left key. As in Experiment 1, they were instructed to respond to the tone on the left side by pressing the left key and to the right tone by pressing the right key. This set-up leads to a spatial incompatibility between the stimulus and the corresponding effector (i.e., the finger) and between the effector and the response location (i.e., the key) in the manual task, whereas stimulus and response locations remain spatially compatible. For example, an imperative auditory stimulus on the left required a response with the left key, which is, however, operated by the right finger. More important, in the dual-task condition the effector in the manual task is incompatible to the saccade direction in the saccade task. This stimulus–effector incompatibility in the manual task is hypothesized to lead to cross-task response-code conflict.

Crossed-hands manipulations are known to affect performance only slightly, because responses are mainly spatially coded, that is, in terms of the spatial response location (Heister, Schroeder-Heister, & Ehrenstein, 1990; Lu & Proctor, 1995; Umiltà & Nicoletti, 1990). As far as spatial separation allows a response discrimination, conflicting effector codes modulate performance only to a small degree (e.g. Hommel, 1993; Worringham & Kerr, 2000) or are relevant only in a later stage of response execution, when spatial codes are translated into specific motor programs. In the context of the present experiment, the crossed-hands manipulation should introduce a relatively moderate amount of response-code conflict in the dual-task situation, whereas in Experiment 3, we further increased the degree of response-code conflict.

Method

Participants. A new group of 12 right-handed participants took part in this experiment. The group consisted of 9 women and 3 men. Mean age was 23 years ($SD = 3.10$), ranging from 19 to 29.

Stimuli, apparatus, procedure, and design. Except for the demand to cross the hands (see above), all other aspects, including the task instruction, were exactly as in Experiment 1.

Results and Discussion

Because of blinks or measurement error, we discarded 11.63% of trials of the saccade task in single blocks and 9.12% of trials in the dual-task condition. In the manual task in single blocks, 4.01% of trials with erroneously executed simultaneous saccades were excluded.

Table 1 shows the mean RTs of saccades and manual responses in single- and dual-task conditions. An ANOVA yielded a significant main effect for task condition (single vs. dual), $F(1, 11) = 10.81$, $p = .007$, $\eta_p^2 = .50$, indicating longer RTs in the dual-task condition than in the single-task condition. The main effect of modality (saccade vs. manual response) was also significant, $F(1, 11) = 279.14$, $p < .001$, $\eta_p^2 = .96$. RTs for saccades were generally shorter than RTs for manual responses (208 ms vs. 446 ms). The interaction of modality and task condition was significant, $F(1, 11) = 8.19$, $p = .015$, $\eta_p^2 = .43$. Dual-task costs were more pronounced in manual responses as compared with saccades (54 ms vs. 21 ms). Separate paired t tests (one-tailed) revealed that RTs of manual responses were significantly longer in the dual-task condition than in the single-task condition, $t(11) = 3.30$, $p < .004$. Supporting the trend already found in Experiment 1, the same holds for the RTs of the saccades, $t(11) = 2.78$, $p = .009$. Saccade amplitudes differed as a function of task condition, $t(11) = 2.26$, $p = .045$, with amplitudes being about 0.17° shorter under dual-task conditions.

Errors in manual responses occurred only in dual-task conditions ($M = 9.7\%$, $SD = 4.9\%$). Directional errors of saccades almost never occurred. The saccade was initiated earlier than the manual response in 97.8% of the dual-task trials, whereas the remainder consisted of reversals from this sequence. Eliminating these reversals in the analysis did not change the pattern of results.

In summary, RTs in the manual task were prolonged when a simultaneous saccade had to be performed. Furthermore, we also

found that performance of the manual responses suffered more from dual-task demands than did the saccades. Most important, however, significant dual-task costs could also be observed for the saccade.

Experiment 3

In Experiment 3, participants were asked to cross their hands in the manual task, but instead of introducing stimulus–effector incompatibility, we instructed participants to respond with the hand that anatomically corresponded to the side of the imperative auditory stimulus, leading to S-R location incompatibility in the manual task (for a similar manipulation in another context, see Roswarski & Proctor, 2003; Wascher, Schatz, Kuder, & Verleger, 2001). For example, an imperative auditory stimulus on the left required a response with the left hand, which, however, was placed on the right key.

Unlike Experiment 2, in which the instruction referred to the preferred spatial response code, namely, the response locations, here the instruction highlights the effector, leading to a reversed (i.e., incompatible) spatial relation between the stimulus and the response key in the manual task. Because the preferred spatial response codes are now incompatible across both tasks in dual-task conditions, we should introduce even more response-code conflict.

Method

Participants. Twelve new participants (10 women and 2 men) took part in this experiment. Mean age was 24 years ($SD = 7.39$), ranging from 19 to 45. Eleven of the 12 participants were right-handed.

Stimuli, apparatus, procedure, and design. Participants were asked to cross hands for the manual task, but unlike Experiment 2, they were instructed to respond with the index finger of the hand that corresponds to the imperative auditory stimulus. All other aspects of the manual as well as the saccade task remained as in Experiment 1.

Results and Discussion

Because of blinks or measurement error, we discarded 2.95% of trials of the saccade task in single blocks and 4.95% of trials in the dual-task condition. In the manual task in single blocks, 5.90% of trials with erroneously executed simultaneous saccades were excluded.

Table 1 shows the mean RTs of saccades and manual responses in single- and dual-task conditions. An ANOVA yielded a significant effect of task condition (single vs. dual), $F(1, 11) = 53.22$, $p < .001$, $\eta_p^2 = .83$, indicating longer RTs in the dual-task condition than in the single-task condition. The effect of modality (saccade vs. manual response) was also significant, $F(1, 11) = 73.49$, $p < .001$, $\eta_p^2 = .87$. RTs for saccades were generally shorter than RTs for manual responses (315 ms vs. 758 ms). The interaction of modality and task condition was significant as well, $F(1, 11) = 11.35$, $p = .006$, $\eta_p^2 = .51$. Dual-task costs were more pronounced in manual responses than in saccades (255 ms vs. 138 ms). Separate paired t tests (one-tailed) revealed that RTs of the manual responses were significantly longer in dual-task than in the single-task conditions, $t(11) = 6.46$, $p < .001$. The same holds for

the RTs of the saccades, $t(11) = 6.18$, $p < .001$. Saccade amplitudes differed as a function of task condition, $t(11) = 3.48$, $p = .005$, with amplitudes being about 0.27° shorter under dual-task conditions.

Errors in manual responses occurred only in dual-task conditions ($M = 19.2\%$, $SD = 8.6\%$). Directional errors of saccades almost never occurred. The saccade was initiated earlier than the manual response in 98.9% of the dual-task trials, whereas the remainder consisted of reversals. Eliminating these reversals did not change the pattern of results.

As in Experiment 2, the results clearly show that performance of both saccades and manual responses suffered from dual-task conditions. These findings corroborate the claim that both effector systems influence each other when participants have to perform simultaneous responses.

An interesting observation was that in this experiment, as in Experiment 2, a small but significant shortening of saccade amplitudes in dual-task conditions was found. Therefore, not only saccade latencies but also saccade amplitudes were modulated as a function of processing demands. A second interesting observation was that RTs of the saccades in single-task conditions were about 47 ms higher in Experiment 3 than in Experiments 1 and 2 (see Table 1). Note that the task was the same across experiments, and it was arranged blockwise. We can therefore only speculate about possible reasons of this effect. The high error rates and long RTs in the dual-task blocks of Experiment 3 suggest that participants were engaged in a difficult task. It is therefore possible that the participants tried to keep in mind the demands of the dual-task conditions even when they had to perform the single-task blocks, subsequently increasing working memory load. Alternatively, a random sampling error might explain this between-experiment difference as well.

Experiment 4

Experiment 4 was conducted to further corroborate the claim that response-code conflict is the underlying mechanism of the observed dual-task costs in Experiment 3. If this reasoning is true, then spatially compatible responses across tasks should cause fewer dual-task costs, even though the S-R mappings in each of the two tasks are both spatially incompatible. To explicitly test this prediction, we asked participants to execute both saccades and manual responses in the opposite direction of the imperative auditory stimulus (for a similar manipulation in another context, see Duncan, 1979, and Vu & Proctor, 2006). For example, an imperative auditory stimulus on the left required a response with the right hand, which is placed on the right key, and/or with a saccade to the right. Unlike Experiments 2 and 3, participants were not asked to cross hands, because there is no anatomical equivalent of such a setting for the eyes.

Method

Participants. Twelve new participants (9 women and 3 men) took part. Mean age was 23 years ($SD = 4.39$), ranging from 21 to 28. All participants were right-handed.

Stimuli, apparatus, procedure, and design. Participants were asked to operate the right key with the right index finger and the left key with the left index finger. In both the manual and the

saccade task, they were instructed to respond with the key and/or the saccade that is spatially incompatible to the imperative auditory stimulus. All other aspects of the manual as well as the saccade task remained as in the previous experiments.

Results and Discussion

Because of blinks or measurement error, we discarded 6.00% of trials of the saccade task in single blocks and 3.00% of trials in the dual-task condition. In the manual task in single blocks, 6.30% of trials with erroneously executed simultaneous saccades were excluded.

Table 1 shows the mean RTs of saccades and manual responses in single- and dual-task conditions. An ANOVA yielded a significant effect of task condition (single vs. dual), $F(1, 11) = 29.94$, $p < .001$, $\eta_p^2 = .73$, indicating longer RTs in the dual-task condition than in the single-task condition. The effect of modality (saccade vs. manual response) was also significant, $F(1, 11) = 81.25$, $p < .001$, $\eta_p^2 = .88$. RTs for saccades were generally shorter than RTs for manual responses (283 ms vs. 561 ms). The interaction of modality and task condition was significant as well, $F(1, 11) = 12.16$, $p = .005$, $\eta_p^2 = .53$. Dual-task costs were more pronounced in manual responses than in saccades (134 ms vs. 26 ms). Separate paired t tests (one-tailed) revealed that RTs of the manual responses were significantly longer in dual-task than in single-task conditions, $t(11) = 4.79$, $p < .001$. The same holds for the RTs of the saccades, $t(11) = 2.34$, $p = .019$. Saccade amplitudes did not differ as a function of task condition, $t(11) = 1.20$, $p > .10$.

Errors in manual responses occurred only in dual-task conditions ($M = 14.3\%$, $SD = 14.8\%$). Directional errors of saccades did not significantly differ between single-task ($M = 10.7\%$, $SD = 9.1\%$) and dual-task conditions ($M = 12.4\%$, $SD = 7.5\%$; $t < 1$). The saccade was initiated earlier than the manual response in 99.1% of the dual-task trials, whereas the remainder consisted of reversals. Eliminating these reversals did not change the pattern of results.

As in Experiments 2 and 3, the results clearly show that performance of both saccades and manual responses suffered from dual-task conditions. These findings again corroborate the claim that both effector systems influence each other when participants perform simultaneous responses. However, here we could not find a significant modulation of saccade amplitudes, which probably results from overall processing ease based on the spatial compatibility between both responses.

Comparison Across Experiments

Experiment 1 Versus Experiment 2: Effect of Stimulus–Effector Incompatibility

Experiments 1 and 2 differed with respect to the crossing of the hands, leading to stimulus–effector incompatibility in the manual task of Experiment 2 relative to Experiment 1. To test the effect of stimulus–effector compatibility, we ran a mixed-design ANOVA, including experiment (1 vs. 2) as an additional independent variable. The interaction of task condition (single vs. dual) and experiment was not significant, $F(1, 22) < 1$, indicating that overall dual-task costs did not differ between the experiments. However,

the interaction of modality and experiment was significant, $F(1, 22) = 15.85$, $p < .001$, $\eta_p^2 = .42$, indicating that the difference between RTs of saccades and manual responses increased from Experiment 1 to Experiment 2 (163 ms vs. 238 ms). Post hoc comparisons did not yield significant differences in saccadic RTs between experiments, neither in single-task conditions nor in dual-task conditions, both $t_s(22) < 1$. However, manual RTs were significantly longer in Experiment 2, in single-task conditions as well as in dual-task conditions, $t(22) = 3.48$, $p = .002$, and $t(22) = 2.48$, $p = .021$, respectively. The three-way interaction of task condition, modality, and experiment was not significant, $F(1, 22) < 1$. In Experiment 2, more errors occurred in the manual task in dual-task conditions than in Experiment 1 (2.58% vs. 9.71%), $t(22) = 4.79$, $p < .001$. Taken together, these data suggest that stimulus–effector incompatibility in the manual task increases the degree of response-code conflict and thus the observed dual-task costs. Particularly, we found significant dual-task costs in the saccades.

Experiment 2 Versus Experiment 3: Effect of S-R Location Incompatibility

The role of S-R location compatibility in the manual task was tested in Experiment 3, in which the instruction referred to the hand rather than the response key location. We therefore compared the results from Experiments 2 and 3. The interaction of task condition and experiment was significant, $F(1, 22) = 29.78$, $p < .001$, $\eta_p^2 = .58$, indicating that dual-task costs increased from Experiment 2 to Experiment 3. Also the three-way interaction of task condition, modality, and experiment was significant, $F(1, 22) = 5.47$, $p = .029$, $\eta_p^2 = .20$, indicating that the interaction of task condition and modality is more pronounced in Experiment 3 than in Experiment 2. RTs of the saccades in single-task conditions were significantly longer in Experiment 3 than in Experiment 2, $t(22) = 2.65$, $p = .015$. The same holds for RTs of saccades in dual-task conditions, $t(22) = 4.86$, $p < .001$. RTs of the manual responses in single-task conditions were significantly longer in Experiment 3 than in Experiment 2, $t(22) = 3.67$, $p = .001$. The same holds for RTs of manual responses in dual-task conditions, $t(22) = 5.65$, $p < .001$. The error rate in the manual task in dual-task conditions was higher in Experiment 3 than in Experiment 2 (19.20% vs. 9.71%), $t(22) = 9.23$, $p = .001$. Taken together, these data indicate that the introduction of S-R location incompatibility led to a substantial increase of dual-task costs not only in the manual RTs but also in the saccade RTs, suggesting that response-code conflict even further increased in Experiment 3 relative to Experiment 2.

Experiment 3 Versus Experiment 4: Effect of Response–Response Compatibility in the Context of Incompatible S-R Mappings

The role of response–response compatibility was tested in Experiment 4, in which the response codes across tasks were spatially compatible, but S-R mappings in each task were incompatible. Because a confusion of response codes should not be harmful in such a setting as compared with Experiment 3, this should result in a decrease of dual-task costs. Indeed, a comparison of the results from both experiments revealed that the interaction of task condi-

tion and experiment was significant, $F(1, 22) = 14.45, p = .001, \eta_p^2 = .40$, indicating that dual-task costs decreased from Experiment 3 to Experiment 4. Also the interaction of modality and experiment was significant, $F(1, 22) = 7.47, p = .012, \eta_p^2 = .25$, indicating that the RT difference between manual and saccade responses was greater in Experiment 3. The three-way interaction of task condition, modality, and experiment was not significant ($F < 1$).

In single-task conditions, RTs of the saccades were numerically but nonsignificantly longer (23 ms) in Experiment 4 compared with Experiment 3 ($t < 1$), but significantly so in dual-task conditions, $t(22) = 2.13, p = .045$. RTs of the manual responses in single-task conditions were significantly shorter in Experiment 4 than in Experiment 3, $t(22) = 2.21, p = .037$. The same holds for RTs of manual responses in dual-task conditions, $t(22) = 3.20, p = .004$. The error rate in the manual task in dual-task conditions was reduced in Experiment 4 compared with Experiment 3 (14.32% vs. 19.20%), but this difference was not significant ($t < 1$). Taken together, these data indicate that spatial compatibility between both responses led to a decrease of dual-task costs, which was predicted by the assumption of response-code conflict as an underlying mechanism of the dual-task costs observed in Experiments 2 and 3.

Analysis of Interresponse Intervals (IRIs)

To further limit the scope of several possible explanations, we analyzed the dependency of the IRI on the RT of the saccade in dual-task conditions across all experiments. To this end, the average RT of the manual responses was computed as a function of the RT of the saccade within its own distribution. Specifically, the RTs of the saccades were ranked for each participant and divided into four bins (i.e., fastest to slowest trials). Trials in which RTs of the saccades were longer than RTs of the manual responses were excluded. Then the RTs of the manual responses corresponding to the saccades in each quartile were averaged. The mean across participants was then computed. Figure 1 presents the mean RTs

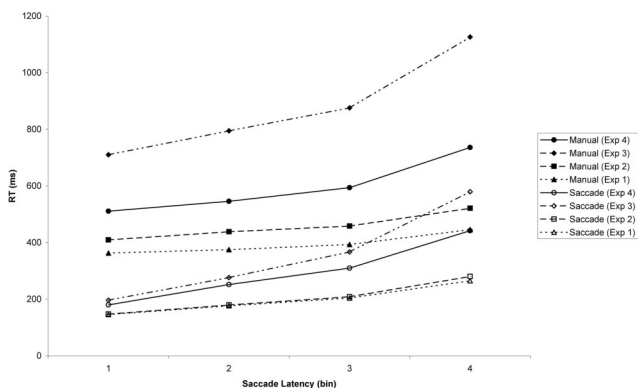


Figure 1. Response times (RTs) of the saccades and the manual responses (in milliseconds) as a function of saccade RT quartiles (Bins 1–4) across all experiments. Note that the data points for the saccade RTs represent the arithmetic mean in the respective quartile, whereas the overall slope depends on the dispersion of the RTs. The difference between the RTs of the saccades and manual responses for each experiment represents the interresponse interval.

for the saccades and manual responses for all experiments as a function of the quartile in which the corresponding RT of the saccade fell.

Across all experiments, the positive slope of the manual RT distribution shows that an increase of the RTs of the saccades was associated with an increase of RTs of the manual responses. Overall, the IRI slightly but significantly decreased as the RTs of the saccades increased, $F(3, 132) = 2.92, p = .037, \eta_p^2 = .06$. Furthermore, the mean IRI varied as a function of experiment, $F(3, 44) = 12.65, p < .001, \eta_p^2 = .46$. The dependency of the IRI on the RTs of the saccades did not significantly differ between experiments, $F(9, 132) = 1.66, p > .10$. In summary, these data show that the IRI is neither constant within nor across the experiments.

An analysis of intraindividual correlations of RTs of the saccades and the manual responses for the dual-task condition corroborated these observations: In each of the experiments, we found significant positive correlations ($p < .05$) for at least two thirds of the participants, ranging from .266 to .939 (mean $r = .45$ across all 48 participants).

General Discussion

The aim of this study was to investigate the mechanisms of crosstalk in dual-task performance. To this end, we examined simultaneously performed saccades and manual responses and manipulated the degree of between-task response-code conflict. More specifically, we had participants respond to a common left or right imperative auditory stimulus with a key press, a saccade, or both. In Experiment 1, the response codes across and the S-R mappings in both tasks were always compatible. In Experiment 2, a crossed-hands manipulation for the manual task introduced stimulus–effector incompatibility in the manual task, leading to an incompatibility between effector-based response codes in the manual task and the spatial response codes in the saccade task. In Experiment 3, participants also had to cross hands but were asked to respond with the effector that corresponds to the imperative auditory stimulus in the manual task (S-R location incompatibility), leading to incompatible spatial response codes between both tasks. In Experiment 4, the response codes across both tasks were compatible, but the S-R mappings in each task were incompatible.

Across the four experiments, we found clear dual-task costs in the manual responses. Furthermore, all experiments showed that the dual-task requirements affected manual responses more markedly than saccades. This asymmetric pattern of dual-task costs can be explained as a result of the highly trained and natural guidance of the gaze toward objects that are spatially compatible to imperative auditory stimuli, resembling a sudden visual orientation in response to auditory stimulation (e.g., Zambardi, 2002). Most important, however, the saccade RTs were prolonged in dual-task conditions, particularly in Experiments 2, 3, and 4. Although in the vast majority of dual-task trials the saccade was the first of the two responses, clear dual-task costs for the saccades were observed. These findings are in line with recent research in the context of PRP paradigms, showing that dual-task costs can also be found for the first of two concurrently performed tasks (i.e., backward crosstalk; e.g., Hommel, 1998; Logan & Delheimer, 2001; Miller, 2006).

Relation to Previous Studies

Previous studies in the context of pointing usually found an increase of the RTs of the saccades but no prolongation of the RTs of the manual responses (e.g., Mather & Fisk, 1985). The main difference with our series of experiments is that in these studies, both movements are directed to a common object. This *per se* involves a coupling of both movements, because visual information is used to effectively perform the manual pointing movement. It is therefore likely that in these previous studies a conjoint response selection has been made for both effector systems before the execution of the saccade that led to only a short delay of the saccade in dual-task conditions compared with single-task conditions (Pashler et al., 1993). Here, we studied on a more general level to what extent saccades and manual responses interact even when they are spatially separated and are also of another type (ballistic saccades vs. key presses with an index finger). As an alternative to the key press responses we used, manual pointing movements might at first sight seem more similar to saccades in terms of the involvement of a spatial displacement. However, pointing movements do not show the typical velocity profile of saccades (e.g., Battaglia-Mayer et al., 2000), and the higher complexity of pointing movements when they are not aimed at the same object as the saccade would probably further increase manual RTs. This would undermine our aim to implement comparable processing demands for both effector systems. Only at least approximately comparable demands ensure that dual-task costs cannot be simply explained in terms of the difficulty of execution-related processes of the individual responses.

Previous studies that did not involve saccades and manual responses to one common object found no dual-task costs (Bekker et al., 1994), dual-task costs only for manual responses (Hodgson et al., 1999), or a rather inconclusive data pattern, namely, that RTs of the saccades increased with shorter SOAs, whereas RTs of the manual responses slightly decreased (Pashler et al., 1993). However, in these studies the saccade task involved a visual stimulus, consequently leading to high input–output modality compatibility (cf. Hazeltine et al., 2006) for the saccade task as compared with the manual task, which may have led to the somewhat inconsistent data patterns. Here, we balanced input–output modality pairings by using one imperative auditory stimulus for both responses, resulting in comparable processing demands for both responses. On the basis of the present findings, it seems that saccades and manual responses cannot generally be initiated independently at the same time. Although we exclusively used auditory stimuli, it is likely that similar crosstalk mechanisms also play a role in saccades to visual stimuli, but the input–output modality compatibility for the saccade task in such a design might reduce the overall amount of dual-task costs for the saccades.

Mechanisms of Crosstalk in a Dual-Task Paradigm

Across experiments, we systematically varied the degree of response-code conflict to investigate the mechanisms of dual-task performance. In Experiment 1, no potential for response-code conflict was introduced because both responses were always spatially compatible. In Experiment 2, however, stimulus–effector incompatibility was introduced for the manual task. Previous research suggests that this only moderately affects performance,

because manual responses are mainly coded spatially (Proctor & Vu, 2006). We reasoned that in the dual-task situation, the resulting incompatibility of the effector-based response code in the manual task and the spatial response code in the saccade task should influence dual-task performance, but only to a relatively modest degree. The comparison of Experiments 1 and 2 showed that although overall dual-task costs were not much higher in Experiment 2, the discrepancy between RTs in the saccades and manual responses increased. Additionally, the increase in error rates rules out the notion of a speed–accuracy trade-off. This modulation of the performance pattern in dual-task conditions shows that the introduction of a relatively modest degree of response-code conflict via incompatible effector codes in the manual task already modulated the pattern of dual-task performance.

In Experiment 3, the incompatibility of the spatial response codes across both responses affected the pattern of dual-task costs even more markedly. Compared with the previous experiments, not only the difference between RTs of the saccades and manual responses increased, but in addition the overall amount of dual-task costs increased, being more than four times higher than in the previous experiments. This shows that the introduction of a quite substantial degree of response-code conflict via incompatible spatial codes in the manual task severely affected dual-task performance.

The consequences of these effects of response-code conflict can be even further specified. A look at the systematic and quite substantial increase in error rates from Experiment 1 to Experiment 3 hints at a possible mechanism underlying the increased dual-task costs, namely, an increase of response-code confusability. This hypothesis is further corroborated by Experiment 4. The notion of response-code confusability would predict that in this experimental set-up in which both responses were incompatible to the imperative stimulus (but therefore spatially compatible across tasks), dual-task costs should be reduced compared with in Experiment 3, because a confusion of response codes is less harmful in such a design. This prediction was confirmed by the data in Experiment 4.

It is interesting to note that in all experiments the dual-task costs were greater for the manual responses as compared with the saccades. This means that the prolongation of saccade RTs does not simply propagate only onto the manual responses. Instead, the greater dual-task costs for manual responses suggest that the activation of response codes in both tasks require a shared representation. This interpretation is in line with previous research suggesting that manual and oculomotor responses are represented in a common supramodal representation of attentional space (Hodgson et al., 1999), where a confusion of response codes might occur. Evidence from lesion and brain imaging studies suggests that such a supramodal representation for eye–hand interaction is mainly controlled by a parieto–cerebellar network (e.g., Battaglia-Mayer et al., 2000; Brown, Kessler, Hefter, Cooke, & Freund, 1993; Ramnani, Toni, Passingham, & Haggard, 2001). However, these studies addressed eye–hand coordination in the context of reaching, where both movements are coordinated with the aim to manipulate a common object. Further research is therefore needed to clarify whether the underlying mechanisms of reaching movements might transfer to the present study.

In summary, the mechanism that underlies crosstalk in the present study could be specified as response-code conflict, and we

assume that a higher degree of such a conflict leads to an increased probability of response-code confusions. Such a basic phenomenon might also transfer to more natural and complex settings, because people almost constantly move their eyes and hands concurrently, especially during tasks like hand writing, typing, human-computer interaction, and driving a vehicle.

Theoretical Alternatives: Capacity Sharing and Bottlenecks

In the following, we discuss several alternative theoretical frameworks to the notion of crosstalk on the basis of the IRI analyses across experiments.

Classic accounts of capacity sharing. First, traditional accounts of shared capacity (e.g., Kahneman, 1973) would predict that worse performance in one task should lead to enhanced performance in the other task. However, the data clearly do not support this notion, because the distribution of the RTs of the manual responses as a function of the RTs of the saccades revealed that dual-task trials with long RTs of the saccades were also associated with long RTs of the manual responses.

Multiple resource models. Second, multiple resource models (e.g., Wickens, 1984) do not represent a suitable theoretical framework. First, the separation of effector systems for the responses should imply separate output-based resources, so that only minimal dual-task costs should occur. Second, input conflict should not arise, because there are no competing stimuli within the same modality domain as a result of the common auditory stimulus for both responses. However, we did observe clear dual-task costs in all experiments, a finding that is at odds with the notion of separate resources for both tasks.

Limited-capacity bottleneck model. As the results show, in Experiment 1 we found significant dual-task costs for the manual task, but not—at least not significantly—for the saccade task. This pattern would be in line with the assumption of a central response selection bottleneck (Pashler, 1993, 1994; Welford, 1952). According to this view, the manual RT is prolonged because manual response selection has to wait until the response selection for the saccade is completed. This argument hinges on the assumption that response selection for the saccades occurs first, at least in the majority of trials. However, manual responses in the dual-task conditions were delayed for only about 60 ms, which is not as high as previously observed in other task combinations (Pashler, 1994). It can be speculated whether the time needed for response selection in the manual task is that short because spatial response-code information from the first selection (saccade task) is transferred, subsequently priming the manual response selection. This priming mechanism is possible, because, in Experiment 1, participants knew that both responses would always be spatially compatible. In the remaining experiments, we also found more dual-task costs for the manual responses compared with the saccades, as would be predicted by a response selection bottleneck. However, here we have clear evidence for a prolongation of the RTs of the saccades in dual-task conditions, which is more difficult to explain within the framework of a central response selection bottleneck. Furthermore, the additional increase of the interaction effect of modality and task condition in Experiment 3 is not in line with the notion that the observed prolongation of saccade latencies is due only to an overall unspecific increase of task difficulty.

Central capacity sharing. An alternative class of models is based on the idea of a limited-capacity central decision process that can be shared between simultaneous tasks (e.g., Meyer & Kieras, 1997; Navon & Miller, 2002; Tombu & Jolicoeur, 2003). These models are known to also account for typical patterns of RTs in dual-task and PRP experiments, hence leaving room for an alternative theoretical framing of the data. The fact that we find a mutual influence of both simultaneously performed responses seems to be compatible with the assumption of a parallel central processing of both responses. The crosstalk mechanisms specified above can thus be regarded as the specification of the processes involved in central capacity sharing.

Response Grouping as an Alternative Explanation?

Finally, we consider the possibility of response grouping as an explanation of the data. Fagot and Pashler (1992) conducted a series of experiments in which participants had to initiate a vocal and a manual response to a common visual stimulus. They found evidence for a conjoint response selection, meaning that only one response selection was necessary for both responses. After this conjoint selection, both response execution processes are assumed to start at the same time, leading to “conjoint responding” (Pashler & Johnston, 1989) or “response grouping.” This strategy involves a selection of both responses before the execution of either (De Jong, 1993; Pashler & Johnston, 1989). Response grouping has frequently been observed under various conditions (e.g., Borger, 1963; Pashler, 1994; Ruthruff, Pashler, & Hazeltine, 2003; Ruthruff, Pashler, & Klaassen, 2001; Schuch & Koch, 2006; Ulrich & Miller, 2008). More specifically, the performance of a response sequence is assumed to involve additional processing aimed at sequence construction that occurs after the selection of both responses, but before motor programming (Schuch & Koch, 2006; Verwey, 1994). In the context of the present study, conjoint response selection would therefore predict an independency of the IRI of the RTs of the saccades.

In the present dual-task setting, the same stimulus was relevant for both tasks. Furthermore, both responses involved a comparable space-based response selection mechanism, because we implemented two-alternative forced spatial choice tasks and, unlike previous studies (e.g., Pashler et al., 1993), more balanced S-R modality pairings. Therefore, only the response execution stage clearly differs between both tasks. Thus, one can assume that the RT difference between the saccade and the manual response in single-task conditions solely reflects the temporal difference between both tasks in response execution. When the response grouping account is true in the context of the present study, a strong prediction would be that regardless of the RTs of the first response (the saccade), the interval between both responses should be constant. More precisely, this interval should be in the range of the RT difference between the saccade and the manual response in single-task conditions, because this interval reflects the temporal difference in response execution only. When a conjoint response selection is performed, and the system is only involved in the execution of a prespecified response sequence, there is no reason why the IRI should vary under any condition.

However, three observations disconfirm the idea of response grouping in the present experiments. First, the IRI was not independent of the RTs of the first response (the saccade), but a perfect

grouping of responses should lead to a constant IRI, regardless of the RT of the first response. Second, if we interpret the difference between RTs of saccades and manual responses in the single-task condition in Experiment 1 as an index of the time difference in response execution (see above), this difference should be the same as the IRI in dual-task trials, given the response grouping account is true. However, in Experiment 1 the IRI in dual-task conditions was substantially longer than the difference between the RTs of saccades and manual responses in the single-task blocks. Finally, the IRIs significantly differed between all experiments, proving that the second response cannot always be selected before the execution of the first response.

Taken together, the IRI analyses did not support the notion of response grouping, whereas a central capacity sharing account offers the most convincing explanatory framework for the present data.

Conclusions

In summary, the present experiments revealed mutual crosstalk in the simultaneous performance of saccades and manual responses. The introduction of a modest (Experiment 2) and substantial (Experiment 3) degree of between-task crosstalk based on conflicting response codes systematically modulated the pattern of dual-task costs accordingly. The increase of errors in the dual-task conditions from Experiment 1 to Experiment 3, as well as the decrease of dual-task costs in Experiment 4 compared with Experiment 3, suggests that the underlying mechanism of crosstalk here is the confusability of response codes between tasks.

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Received October 1, 2007

Revision received July 17, 2008

Accepted July 20, 2008 ■