Cognition 132 (2014) 30–43

Contents lists available at ScienceDirect

Cognition

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

Who is talking in backward crosstalk? Disentangling response- from goal-conflict in dual-task performance

Markus Janczyk [a,*], Roland Pfister [a], Bernhard Hommel [b], Wilfried Kunde [a]

[a] University of Würzburg, Department of Psychology III, Röntgenring 11, 97070 Würzburg, Germany
[b] Leiden University, Department of Psychology, Cognitive Psychology Unit, Wassenaarseweg 52, 2333 AK Leiden, The Netherlands

ARTICLE INFO

Article history:
Received 9 October 2012
Revised 13 February 2014
Accepted 4 March 2014

Keywords:
Dual-tasking
Action effects
Backward crosstalk
Ideomotor theory
Goals

ABSTRACT

Responses in the second of two subsequently performed tasks can speed up compatible responses in the temporally preceding first task. Such backward crosstalk effects (BCEs) represent a challenge to the assumption of serial processing in stage models of human information processing, because they indicate that certain features of the second response have to be represented before the first response is emitted. Which of these features are actually relevant for BCEs is an open question, even though identifying these features is important for understanding the nature of parallel and serial response selection processes in dual-task performance. Motivated by effect-based models of action control, we show in three experiments that the BCE to a considerable degree reflects features of intended action effects, although features of the response proper (or response-associated kinesthetic feedback) also seem to play a role. These findings suggest that the codes of action effects (or action goals) can become activated simultaneously rather than serially, thereby creating BCEs.

1. Introduction

Humans have considerable difficulty performing multiple tasks at once, so that multi-tasking typically results in performance decrements in at least one of the tasks. Such performance costs have been attributed to serial processing in one or more of the involved processing stages. Serial models often identify the selection of appropriate responses as such a serial processing stage, while perceptual or motor execution processes are assumed to be carried out in parallel to other processes (e.g., Pashler, 1994; Pashler & Johnston, 1989; Welford, 1952; see Fig. 1a). However, a number of empirical observations have casted some doubts on the validity of serial models. The present study aimed at revisiting the serial-stage assumption by better characterizing the supposedly serial processes, if any. We did so by making use of the backward crosstalk effect in dual-task situations.

1.1. Backward crosstalk in dual-tasking

In addition to general dual-task performance costs, specific task demands and characteristics determine how well two or more tasks go together. For example, mental rotation is facilitated if preceded by, or performed simultaneously with a manual rotation in the same direction (Wexler, Kosslyn, & Berthoz, 1998; Wohlschläger & Wohlschläger, 1998). It is even more intriguing that such inter-task facilitation works in the reverse direction as well: Responding in the first-performed task is facilitated if the features of the corresponding response overlap with features of the response in the subsequently performed second task (e.g., Hommel, 1998). This is particularly interesting because it suggests that features of the second response are activated before or while the first response

* Corresponding author. Tel.: +49 (0)931 3183845.
E-mail address: markus.janczyk@uni-wuerzburg.de (M. Janczyk).

http://dx.doi.org/10.1016/j.cognition.2014.03.001
0010-0277/

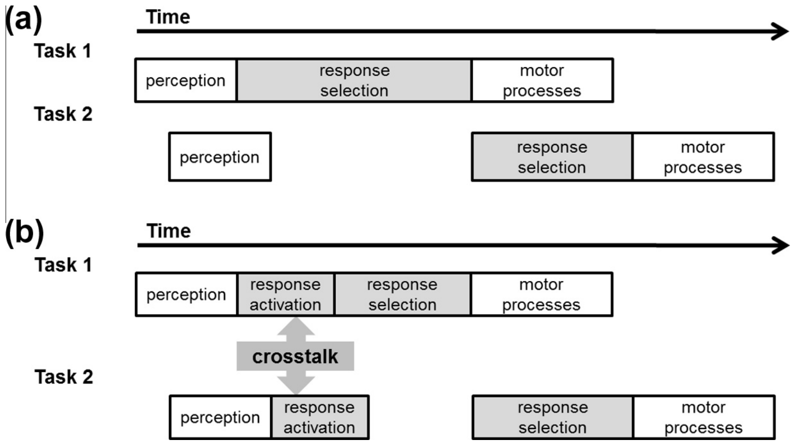

Fig. 1. Schematic of information-processing models that revolve around a central response selection bottleneck. (a) The model of Pashler (1994) assumes a unified stage of central response selection that can only be occupied by one task at a time. If Task 1 response selection is on the way, Task 2 response selection must wait and hence cannot affect Task 1 response selection or related perceptual processes. (b) According to Hommel (1998) and Lien and Proctor (2002), central stages may consist of two sub-stages: A first sub-stage of response *activation* still proceeds in parallel with other stages and is the place where crosstalk effects may arise. A second stage of response *selection* is capacity limited and drives one of the activated responses above threshold.

is being selected, which challenges the idea that response selection operates strictly serially. Apparently, the second response "works back" on the first response, which is why effects of Task 2 on Task 1 performance have been coined "backward crosstalk effects" (BCEs).

The first demonstration of a BCE was reported by Hommel (1998): A colored letter stimulus was presented in each trial and participants carried out a manual left/right response (R1) to the color of this letter and a vocal response (R2; the German words for "left" or "right") to the letter identity. Response times (RTs) in the first task were shorter when R1 and R2 were compatible (e.g., when pressing the left key was followed by saying "left") as compared to incompatible relations. Later studies showed BCEs with various kinds of feature overlap (e.g., Ellenbogen & Meiran, 2008, 2011; Hommel & Eglau, 2002; Logan & Delheimer, 2001; Logan & Gordon, 2001; Logan & Schulkind, 2000; Miller, 2006), ranging from physical features, such as spatial correspondence (e.g., Lien & Proctor, 2000), to rather abstract features, such as if responding in the first task is systematically delayed when the second task requires withholding a response (Miller, 2006) or influences of Task 2 response force requirements on Task 1 responses (Miller & Alderton, 2006).

Accommodating the phenomenon of BCEs requires the assumption of some degree of parallel processing even at stages typically assumed to operate serially.[1] Hommel (1998) subdivided central stages into a parallel response *activation* sub-stage that is followed by a (perhaps strictly serially operating) response *selection* sub-stage (see also Lien & Proctor, 2002; see Fig. 1b). According to that model, Task 2 characteristics can affect Task 1 performance during the response activation sub-stage, thus yielding BCEs. Indeed, there is converging evidence that some of the processes mapping a Task 2 stimulus to its appropriate response are already active, while the same processes are still ongoing for Task 1 (Schubert, Fischer, & Stelzel, 2008).

In most previous demonstrations of BCEs, crosstalk arises between responses that indicate certain classifications of experimental stimuli. Accordingly, most BCEs might best be seen as an instance of response–response conflict (see also Navon & Miller, 1987). In line with this reasoning, Logan and Gordon (2001) suggested that many BCEs are "most likely a response repetition effect" (p. 412). However, this idea immediately poses another question: If BCEs really reflect interactions between features of the two responses, which features are actually critical for producing BCEs?

In the present study we identified the response characteristics/features that eventually give rise to BCEs, i.e., which aspects of the second response "cross-talk" with processing of Task 1. Answering this question was thought to provide deeper insight into which response characteristics can be processed in parallel and how dual-task performance might be improved. To do so, one first needs to dissect responses as used in typical studies on BCEs into different features. In fact, even simple key press responses can comprise various features as we will discuss in the next section.

1.2. Action effects in human performance

At first glance, a simple act such as pressing a key seems to comprise just a few features. For instance, it seems intuitively plausible that pressing the left of two alternative response keys with the left hand, say, is compatible with pressing the left of two other response keys with the right-hand—implying that an entire response can be exhaustively characterized as "left". But a closer look reveals that even a simple key press has more features than that and can thus be cognitively represented in multiple ways. For one, there is the overt behavior resulting from the motor act of key pressing that can be observed from

[1] For a formal theory of parallel processing at central stages, see Tombu and Jolicoeur (2003).

the actor's but also from another person's perspective. Traditionally, this feature is referred to as "response feature" and we will therefore denote the task-relevant feature of observable, overt behavior as "R". In addition, R produces kinesthetic and tactile re-afferent sensory input from pressing the key that is only perceived from the actor's perspective. Further, often visual and perhaps auditory input from the action and its immediate environmental consequences follows. All these kinds of input can be considered effects of R and will therefore be denoted as (features of) "E". Note that in many instances, all these R and E features suggest coding a left key press as "left" and thus are confounded.

However, such effects (Es) are likely to play an important role in action selection. This has been proposed by the *ideomotor approach* to action control, which dates back to philosophical ideas of the 19th century (see Pfister & Janczyk, 2012; Stock & Stock, 2004). Basically, this approach and its more modern versions assume that actions are cognitively represented by codes of their perceivable effects (Greenwald, 1970; Hommel, Müsseler, Aschersleben, & Prinz, 2001). Selecting a response thus means to retrieve and anticipate its sensory effects, which then spread activation to the associated motor pattern. Among other evidence, this assumption has received empirical support by studies on response-effect compatibility (REC; Kunde, 2001). For instance, Kunde had his participants respond to the color of a stimulus by pressing one of four keys. In the compatible REC condition, the key press switched on a spatially corresponding light, while in the incompatible REC condition a non-corresponding light was switched on. Although these action effects occurred only after the key press (i.e., not during response selection), RTs were faster in the compatible REC condition (see also Kunde, Hoffmann, & Zellmann, 2002; Pfister, Kiesel, & Melcher, 2010). Similar REC effects were demonstrated with other and even more abstract relations of responses and effects, such as vocal color responses producing semantically compatible or incompatible color words (Koch & Kunde, 2002) or vocal number responses resulting in visually displayed compatible or incompatible numbers (Badets, Koch, & Toussaint, 2013). Such results are well in line with the ideomotor assumption that action selection operates on codes representing the anticipated sensory features of a given action (cf. Hommel, 2009). This general principle of effect-based action control raises the question of which of the multiple features of actions and their effects are involved in producing BCEs.

Most authors seem to assume that actions are in some way represented by the relative location of the effectors being involved. For instance, Lien and Proctor (2000) had participants press one set of two response keys with the middle and index finger of the left hand and another set with the index and middle finger of the right hand, assuming that pressing the "left" key of the left-hand set and the "left" key of the right-hand set would be compatible. Indeed, BCEs were obtained under these conditions and the direction of the effect was in line with this definition of compatibility. As the two left-hand keys were operated by different fingers, this means that the key locations to which R was made were more important than the

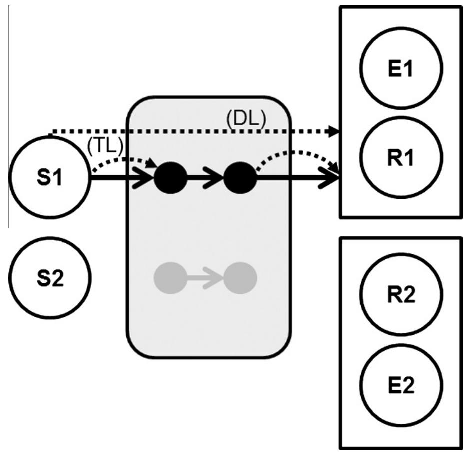

Fig. 2. Illustration of the mechanisms underlying the automatic activation of responses according to Hommel (1998). While a controlled route (bold line) from stimulus to the response explicitly uses an instructed S–R rule, co-activation may arise via two different mechanisms (dotted lines) automatically upon perception of a proper stimulus: First, transient links (TL) use the same S–R rule. Second, in the course of experience direct links (DL) from stimuli to the responses may result. It is, however, unclear, which response features are activated; the overt motor behavior R, or the effects E resulting from R? (See text for more explanation.)

anatomical status of the operating finger – a common observation in compatibility studies (e.g., Wallace, 1971). Now, remember that any given R leads to various Es, such as the proprioceptive feedback from moving the particular finger, the feeling of pressing down a key, and, possibly, ensuing changes on the computer screen. Thus, it might be any of these E-features that were anticipated for response selection (instead or in addition to activating R-features). In other words, the available evidence does not tell us whether BCEs are driven by R-features or E-features. Sketched in a schematic originally developed by Hommel (1998), stimuli can automatically – via direct links (DL) or transient links (TL) – activate either R or E (see Fig. 2 for an illustration). To carefully distinguish these features and to identify the features that are crucial for BCEs was at the core of the present research.

Unfortunately, effects related to kinesthetic or proprioceptive feedback are coupled so tightly to R that it is almost impossible to distinguish between R and these Es experimentally (see, e.g., Stenneken, Aschersleben, Cole, & Prinz, 2002, for work with a deafferented patient). A less invasive approach is to introduce effects in the environment that are coupled to R by an experimental manipulation of R–E relations.[2] Indeed there is increasing evidence that responses can be represented by novel, experimentally induced effects (Elsner & Hommel, 2001),

[2] Given the tight coupling between R and kinesthetic and proprioceptive Es, and the difficulty to manipulate these particular Es in noninvasive ways, in the following we will use to the label R to refer to the representation of both the actual motor response (including the efferent motor signal and the actual muscle movements) and the more intrinsic or "resident" (James, 1890) kinesthetic and proprioceptive action effects and reserve the label E for representations of experimentally introduced, more "remote" effects, such as visual events resulting from the motor behavior. This is for practical purposes only and not meant to deny that kinesthetic and proprioceptive action effects can have the same functional status as visual or other effects.

especially if they are defining the actual action goal (Hommel, 1993). For instance, the otherwise robust advantage of responding simultaneously with homologous rather than non-homologous finger combinations (e.g., Cohen, 1971; Heuer, 1993) can be reversed if actions with homologous fingers lead to different visual effects while actions with non-homologous fingers produce similar effects (Janczyk, Skirde, Weigelt, & Kunde, 2009; for converging evidence see also Kunde, Krauss, & Weigelt, 2009; Kunde & Weigelt, 2005; Mechsner, Kerzel, Knoblich, & Prinz, 2001).

Even more interesting, experimentally induced action effects have been shown to be involved in interference in dual-task situations, as with more or less simultaneous mental and manual rotations. As already mentioned, mental rotations are typically facilitated by preceding or simultaneous manual rotations into the same direction (e.g., Wexler et al., 1998; Wohlschläger & Wohlschläger, 1998). In a recent study, Janczyk, Pfister, Crognale, and Kunde (2012) disentangled the contributions of effector and goal-effect features by combining a manual rotation with an effect rotating in either the same or the opposite direction. Participants performed a mental rotation task followed by the manual rotation, and once attention was directed to the visual effects, facilitation depended on the directional overlap of the mental and the effect rotation, not the manual rotation itself.

1.3. The present study

Given the evidence for a contribution of action effects to both single- and dual-task performance it is interesting to ask whether they may represent the critical response feature that becomes activated automatically and creates BCEs. The present study pursued this question in three experiments in which the overt motor response to Task 1 (R1) was a simple left/right key press with the left hand. The response in Task 2 (R2) was carried out with the right hand and was either a left/right key press (Exp. 1 and 3) or a continuous left/right movement (Exp. 2).

In Experiments 1 and 2, the actual goal in Task 2 was to produce a visual effect (E2): A response-contingent visual event that in one group of participants (Exp. 1) or in one condition (Exp. 2) appeared on the same side as R2 (R–E-compatible condition) and in another group or condition on the opposite side (R–E-incompatible condition). In the R–E-compatible condition, all spatial features of the entire action event, including both R2 and E2, referred to the same relative location. Accordingly, the entire action event would be coded "left" or "right" and affect compatible or incompatible responses in Task 1 accordingly, irrespective of whether the resulting BCE would reflect an impact of R codes, E codes, or both. We thus expected a standard R2–R1 BCE to emerge in this situation with faster Task 1 responses for spatially compatible R2–R1 relations.

The crucial question was what would happen in the R–E-incompatible situation, where a right response would contingently produce an intended action effect on the left side and a left response would contingently produce an intended action effect on the right side. Note that, due to this R–E relationship, a compatible R1–R2 relation (e.g., left key press in Task 1 and left key press in Task 2) implied an incompatible relation between R1 and E2 (left key press in Task 1 and right light flash in Task 2), while incompatible R1–R2 relations implied compatible R1–E2 relations. A comparison of the size and sign of the BCE in R–E-compatible and R–E-incompatible conditions is thus diagnostic for the relative contributions of response and effect features to the BCE. Consider, for instance, that only the E feature would matter: This would mean that the BCE should completely reverse from R–E-compatible to R–E-incompatible conditions.[3] If, in turn, only R features would matter, the compatibility between R2 and E2 should have no impact on the BCE. A probably more realistic outcome is a pattern laying somewhere in between, however. As shown by Hommel (1993) with single-task conditions, people tend to consider multiple spatial relationships when coding their responses. That study was designed to disentangle the degree to which people code their actions in terms of the anatomical status of the active effectors, the effectors' (and keys') relative locations, and the location of the intended action effect. The findings suggest a dominant contribution from the latter source (i.e., action goal), but measurable contributions from the other two variables as well. This indicates that people can weigh the feature codes referring to a given action according to their relative importance (Memelink & Hommel, 2013). If so, we would expect that making R2 and E2 incompatible reduces and perhaps even tends to reverse the BCE in sign without necessarily producing a significantly reversed BCE of the same size as with a compatible R2–E2 relation. In this case, however, the interaction of R1–R2 relation and R2–E2 relation should still be significant. Experiment 3 complements these experiments by coupling both responses with intended visual action effects.

2. Experiment 1

Participants were presented with single letters of varying identity and color as stimuli. Both tasks required a left/right manual key press with the left (Task 1) or the right hand (Task 2). Both responses were thus compatible when both hands performed a key press on the same side but incompatible if the key locations did not match (see Hommel, 1998, and Lien & Proctor, 2000, Exp. 2 and 3, for comparable setups).

Importantly, R2 switched on a light that was located on the left or right side of the screen, and it was this event that participants were asked to produce in Task 2 (the intended action effect or action goal; see Hommel, 1993). For one group of participants, the left/right key press as R2 triggered the light at the corresponding location (rendering it a compatible R2–E2 relation). Here we expected a standard BCE. The critical manipulation was implemented for a second group of participants, where R2 triggered the light on the opposite side (rendering it an incompatible R2–E2 relation). Depending on whether

[3] Throughout the manuscript, we code BCEs according to the spatial relation between R1 and R2, irrespective of the visual effects produced by them.

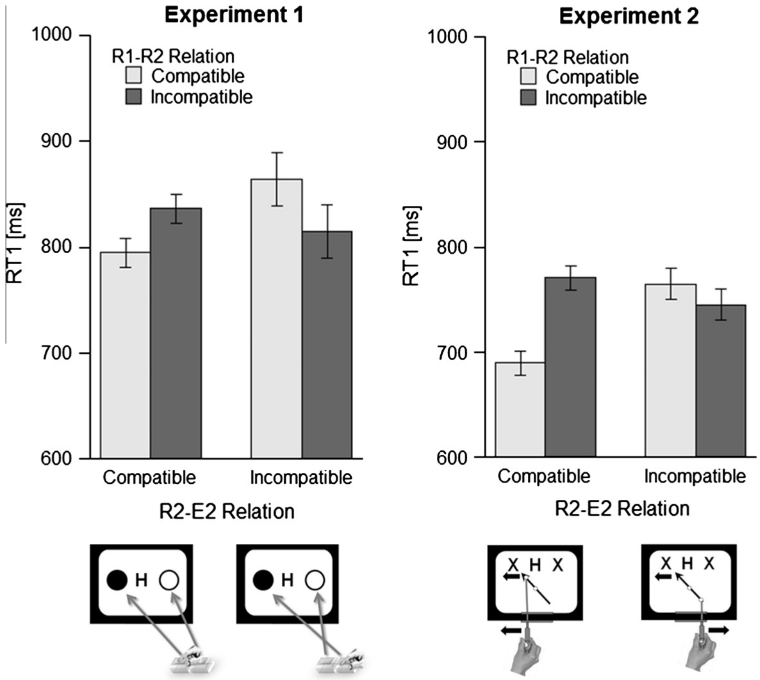

Fig. 3. Mean response times in Task 1 (RT1) of Experiments 1 and 2 as a function of R1–R2 relation and R2–E2 relation. Error bars are within-subjects standard errors, computed separately for each R2–E2 relation (Pfister & Janczyk, 2013). Further, visualizations of the Task 2 responses and corresponding effects in both experiments are provided at the bottom: Target stimuli were the colored letters H and S and R2 was specified by letter identity. In Experiment 1, a key press response with the right index or middle finger either switched on a light on the compatible side of the display (compatible R2–E2 relation) or on the opposite side (incompatible R2–E2 relation). In Experiment 2, the movement of a controller was translated into the movement of a virtual lever either in the same direction (compatible R2–E2 relation) or the opposite direction (incompatible R2–E2 relation).

R2s are coded in terms of the actual response, the intended visual action effect, or a mixture of the two, we expected the BCE to be unaffected, completely reversed, or reliably reduced (and perhaps descriptively reversed), respectively.

2.1. Method

2.1.1. Participants

Thirty-two adults from the Würzburg community (mean age: 25.0 years, SD = 7.9; 24 female) participated for monetary compensation (or course credit). All participants were naïve regarding the hypotheses of the experiment.

2.1.2. Apparatus and stimuli

A standard PC was used for stimulus presentation and response registration. Stimuli were shown against a black background on a 17-in. CRT monitor with a viewing distance of approximately 70 cm. Stimuli were the letters ‘H’ and ‘S’ presented in green or red color. Responses were given via key presses with the index and middle fingers of the left and right hand. Two of the keys were located on the left and two other keys on the right side of the participants. Two circles with a white outline were presented to the left or right of the screen center. The instructions referred to them as “lights” and to “switching them on” (which turned the entire circle white) as the action goal in Task 2.

2.1.3. Procedure

Participants were individually tested in a single session of about 30 min. Each trial began with the presentation of a small fixation cross (1000 ms), which after a 250 ms blank display was replaced by the stimulus. The goal of Task 1 was to respond to the color of the letter by pressing a key with the index- or middle-finger of the left hand (R1); the goal of Task 2 was to respond to the identity of the letter by switching on one of the two lights (E2). For half of the participants, the R2 key press switched on the light on the spatially corresponding side (compatible R2–E2 relation), while for the other half, the R2 key press switched on the light on the opposite side (incompatible R2–E2 relation; see Fig. 3, left panel for an illustration). Response times were measured from stimulus onset until the respective key was depressed (RT1 and RT2) and each correct R2 immediately triggered the corresponding E2.

Performance feedback on both tasks (correct vs. incorrect) was presented after each trial and the next trial started after an inter-trial interval (ITI) of 1000 ms. Specific error messages were displayed if no response was given within 2500 ms, if the response order was reversed, or if both responses were not separated by at least 50 ms (to discourage response grouping; see Hommel, 1998).

Participants received written instructions that emphasized speed while asking to keep errors at a low rate and to prioritize Task 1 over Task 2. Furthermore, participants were explicitly instructed to perform the tasks serially, i.e., to give R1 before R2.

Table 1
Mean RTs (in ms) and percentages error (PE) in Task 1 and 2 of Experiments 1 and 2 as a function of R1–R2 relation and R2–E2 relation. Crosstalk effects were computed by subtracting values from the compatible R1–R2 relation from those in the incompatible R1–R2 relation line-by-line. Crosstalk cannot only go from Task 2 to Task 1 (backward crosstalk effect; BCE), but also from Task 1 to Task 2, and we use the label "forward crosstalk effect" (FCE) for the latter variant.

		R2–E2	Experiment 1 R1–R2 Relation			Experiment 2 R1–R2 Relation		
		Relation	Incompatible	Compatible	BCE/FCE	Incompatible	Compatible	BCE/FCE
RT	Task 1	Compatible	836	795	41	771	690	81
		Incompatible	815	864	−49	745	765	−20
	Task 2	Compatible	1077	1032	45	1125	1042	83
		Incompatible	1048	1114	−66	1130	1155	−25
PE	Task 1	Compatible	2.6	2.8	−0.2	7.5	2.9	4.6
		Incompatible	3.6	2.9	0.7	4.0	5.1	−1.1
	Task 2	Compatible	3.3	4.9	−1.6	6.8	5.4	1.4
		Incompatible	3.8	4.3	−0.5	6.8	8.7	−1.9

2.1.4. Design and analyses

Participants completed 10 blocks of which the first two were regarded practice and excluded from analyses. Each block comprised 32 trials, i.e., eight repetitions of the four combinations resulting from the two letter identities and the two colors, presented in random order. The stimulus–response mappings in both tasks were counterbalanced across participants.

The data were analyzed by means of a 2×2 mixed ANOVA. The (independent) variable 'R2–E2 relation' (compatible vs. incompatible) was manipulated between-subjects and the variable 'R1–R2 relation' (compatible vs. incompatible) was manipulated within-subjects. A compatible R1–R2 relation means that both tasks required a key press on the same side. All trials with wrong response order or without R1 given within 2500 ms were excluded in the first place. Further, 0.3% of the remaining data were excluded as both responses were not separated by at least 50 ms. RT analyses were restricted to trials with two correct responses and outliers were excluded if RTs deviated from the mean of the respective design cell by more than 3 standard deviations (Task 1: 1.19%; Task 2: 1.26%).

2.2. Results

2.2.1. Task 1

Mean RTs for Task 1 are shown in Fig. 3 (left panel; see also Table 1). The interaction was significant, $F(1,30) = 5.07$, $p = .032$, $\eta_p^2 = .14$, whereas both main effects were not, R1–R2 relation: $F(1,30) = 0.04$, $p = .851$, $\eta_p^2 < .01$; R2–E2 relation: $F(1,30) = 0.11$, $p = .740$, $\eta_p^2 < .01$.[4] As indicated by separate *t*-tests (one-tailed), a standard BCE emerged for the compatible R2–E2 relation: Responses were faster if R1 and R2 were compatible, $t(15) = 2.20$, $p = .022$, $d = 0.78$. In contrast, with an incompatible R2–E2 relation the BCE reversed in sign and was no longer significant, $t(15) = 1.38$, $p = .094$, $d = 0.49$. The respective 95% confidence intervals (two-tailed) for the pairwise differences were [1 ms; 82 ms] and [−125 ms; 27 ms]. To further compare the size of the normal and the reversed BCE, we changed the sign of the effect for participants in the incompatible R2–E2 relation group. A *t*-test revealed that the absolute value of the BCE in the compatible R2–E2 group was not significantly different from the absolute value of the reversed BCE in the incompatible R2–E2 group, $t(30) = 0.19$, $p = .852$, $d = 0.07$. Mean error percentages are summarized in Table 1. Their analysis did not reveal any reliable effects, all $Fs \leqslant 1$, all $ps \geqslant .393$.[5]

2.2.2. Task 2

Mean RTs in Task 2 are summarized in Table 1. The qualitative pattern was as in Task 1, and only the interaction reached significance, $F(1,30) = 5.92$, $p = .021$, $\eta_p^2 = .16$. No other effect was significant, R1–R2 relation: $F(1,30) = 0.21$, $p = .653$, $\eta_p^2 = .01$; R2–E2 relation: $F(1,30) = 0.11$, $p = .742$, $\eta_p^2 < .01$. Mean error percentages are summarized in Table 1 and the main effect of R1–R2 relation was significant, $F(1,30) = 4.30$, $p = .047$, $\eta_p^2 = .13$; all other $Fs \leqslant 1.09$, all other $ps \geqslant .305$.

2.3. Discussion

Experiment 1 compared the impact of response-related and effect-related feature crosstalk on the BCE. To this end, we rendered the locations of manual responses (R2) and visual action effects (E2) in the second task compatible or incompatible. For the group with compatible R2–E2 relations, we found a standard R2–R1 BCE. This pattern replicates earlier findings of Lien and Proctor with a similar setup (2000, Exp. 2 and 3; see also Schubert et al., 2008, Exp. 1 and 2), although these authors did not add any visual effects to R2. Importantly, we found this effect to be numerically reversed for the incompatible R2–E2

[4] A notorious problem in interpreting BCEs is response grouping, i.e., when subjects withhold R1 until R2 is executed. To circumvent this problem, some authors restrict their analyses to trials where the inter-response interval (IRI) is larger than, say, 100 or 120 ms (e.g., Ellenbogen & Meiran, 2011; Miller & Alderton, 2006). Restricting our analyses to trials with such IRIs did not change the pattern qualitatively.

[5] Although effects on error data were small and not significant, a numerical speed-accuracy tradeoff is evident in the data. To test for possible implications, we grouped participants according to whether they exhibited such tradeoff or not and entered this grouping variable as an additional between-subject variable into an ANOVA. Importantly, the critical interaction of R1–R2 relation and R2–E2 relation was still significant, $F(1,28) = 5.74$, $p = .024$, $\eta_p^2 = .17$, and was not modified by the grouping variable, as indicated by a non-significant three-way interaction, $F(1,28) = 1.04$, $p = .318$, $\eta_p^2 = .04$.

relation group. This result is in line with previous work on the role of action effects for forward crosstalk effects (Janczyk, Pfister, Crognale et al., 2012). It also reinforces the notion that intended action effects play a crucial role for response selection (Hommel, 1993) and, as a consequence, contribute to crosstalk between tasks. However, the reversed BCE was not significant by itself (although its absolute value was not significantly different compared with the absolute value of the standard BCE). This indicates that other sources, e.g., the location of the manual action or of the corresponding kinesthetic feedback do also influence the BCE. As this observation will occur again in the subsequent experiments, we will get back to it in the General Discussion.

An objection to the present findings might be that we did not observe a main effect of R2–E2 relation in Task 2, which amounts to a failure to replicate previous studies (e.g., Kunde, 2001; Pfister et al., 2010), where responses were commonly faster if being followed by spatially compatible events. It seems reasonable to attribute this failure to replicate to the present implementation of the R2–E2 relation in a between-subjects design. To test this possibility, in Experiment 2 we manipulated R2–E2 compatibility within-subjects, and we further tested whether the findings of Experiment 1 would extend beyond discrete key press responses.

3. Experiment 2

The results of Experiment 1 suggest that the intended action effects were critical for BCEs to a considerable degree, although other features (e.g., the actual motor response) likely also played a role. To further corroborate this finding, we conducted Experiment 2, in which the major change relates to the responses and intended action goals for Task 2. The discrete key press response was changed into a continuous right-hand movement that produced a spatially compatible or spatially incompatible continuous tool movement (see Fig. 3, right panel, for an illustration). Such tool-transformed effects have proven rather salient and difficult to ignore in previous studies (Janczyk, Pfister & Kunde, 2012). In addition, all participants now performed in both R2–E2 relation conditions.

3.1. Method

3.1.1. Participants

Thirty-two adults from the Würzburg community (mean age: 25.3 years, SD = 4.5; 21 female) participated for monetary compensation. All participants were naïve regarding the hypotheses of the experiment.

3.1.2. Apparatus and stimuli

A standard PC was used for stimulus presentation and response registration. Stimuli were shown against a black background on a 17-in. CRT monitor with a viewing distance of approximately 70 cm. Stimuli were the letters ‘H’ and ‘S’ in green or red color, presented horizontally centered in the upper part of the screen. These target stimuli were flanked by two white Xs. Responses in Task 1 were given via key presses with the left index or middle finger on the left/right arrow keys of a standard QWERTZ keyboard. Responses in Task 2 were given via a custom-built controller that was used and described in detail in previous studies (Janczyk, Pfister & Kunde, 2012; Kunde, Müsseler, & Heuer, 2007; Kunde, Pfister, & Janczyk, 2012). In short, participants moved the controller to the left or right using their right hand (R2). This movement was translated to a corresponding movement of a virtual lever with one pivot (E2). The tip of the lever had to point at one of the X (24°) for successful task performance. In one condition, the controller was connected to the upper part of the lever, resulting in a movement of the lever’s tip into the same direction as the hand (compatible R2–E2 relation). In the other condition, the controller was connected to the lower part, thereby reversing the movement direction of the hand (incompatible R2–E2 relation; see Fig. 3, right panel, for an illustration).

3.1.3. Procedure

Participants were tested individually in a single session of about 60 minutes. In order to start a trial, participants had to move the lever to a central position (tolerance: 3°). The start of the trial was then signaled by a click sound (2000 Hz, 50 ms). The target letter appeared 1000 ms later in the upper center of the screen. Task 1 was to respond to the color of the letter with a key press of the left hand (R1) and Task 2 was to move the tip of the lever into the required direction (according to letter identity) so that the tip pointed at one of the flanking Xs. RTs were measured from stimulus onset until the respective left-hand key press (RT1) and until the lever tip deviated from the starting position for more than 3° (RT2). The R2 movement was continuously translated into the corresponding E2 lever movement. Participants were allowed a maximum of 2500 ms to start with R2. As soon as the lever pointed in the direction of an X (24°; tolerance: 9°), this X disappeared whereas the remaining stimuli remained on screen for additional 1000 ms. This period was also used for error feedback that was displayed as in Experiment 1. The next trial started after an ITI of 1500 ms.

3.1.4. Design and analyses

Participants completed 20 blocks, 10 of each R2–E2 relation, with the first two blocks of each relation condition considered training and being excluded from analyses. Each block comprised 32 trials as in Experiment 1. Stimulus–response mappings and order of the two R2–E2 relation conditions were counterbalanced across participants.

The data were analyzed by means of a 2×2 ANOVA with both ‘R2–E2 relation’ (compatible vs. incompatible) and ‘R1–R2 relation’ (compatible vs. incompatible) as within-subjects variables. An R1–R2 relation was considered compatible if a left/right key press was required for R1 and the controller was to be moved to the left/right for R2. All trials with wrong response order or without R1 given within 2500 ms were excluded first. Further, 0.1% of the remaining data were excluded as both responses were not separated by at least 50 ms. RT analyses were restricted to trials with two correct responses and outliers were excluded if RTs deviated from the mean of the respective design cell by more than 3 standard deviations (Task 1: 1.13%; Task 2: 0.94%).

3.2. Results

3.2.1. Task 1

Mean RTs for Task 1 are visualized in Fig. 3 (right panel; see also Table 1). In contrast to Experiment 1, the main effect of R1–R2 relation was significant, $F(1,31) = 9.28$, $p = .005$, $\eta_p^2 = .23$, showing an overall BCE. However, the interaction was also significant, $F(1,31) = 10.04$, $p = .003$, $\eta_p^2 = .24$, while the main effect of R2–E2 relation was not, $F(1,31) = 1.80$, $p = .189$, $\eta_p^2 = .05$. The pattern of results was as in Experiment 1: A significant standard BCE was found with the compatible R2–E2 relation, $t(31) = 4.95$, $p < .001$, $d = 1.24$, while the BCE was numerically reversed and no longer significant with the incompatible R2–E2 relation, $t(31) = 0.94$, $p = .177$, $d = 0.24$ (one-tailed). The respective 95% confidence intervals (two-tailed) for the pairwise differences were [47 ms; 114 ms] and [−62 ms; 23 ms]. The comparison of the size of the BCEs after reversing the sign for the incompatible R2–E2 relation showed a larger BCE for the compatible R2–E2 relation, $t(31) = 3.05$, $p = .002$, $d = 0.76$ (one-tailed).

Mean error percentages are summarized in Table 1 and they mirror the picture emerging from RTs. In contrast to Experiment 1, the interaction was significant, $F(1,31) = 12.39$, $p = .001$, $\eta_p^2 = .29$. The main effect of R1–R2 relation was also significant, $F(1,31) = 14.17$, $p = .001$, $\eta_p^2 = .31$, whereas the main effect of R2–E2 relation was not, $F(1,31) = 0.78$, $p = .384$, $\eta_p^2 = .02$.

3.2.2. Task 2

Mean RTs in Task 2 are summarized in Table 1. The pattern mirrored that obtained in Task 1: The interaction was significant, $F(1,31) = 8.98$, $p = .005$, $\eta_p^2 = .22$, as was the main effect of R1–R2 relation, $F(1,31) = 7.23$, $p = .011$, $\eta_p^2 = .19$. In addition, RTs were significantly faster with the compatible as compared to the incompatible R2–E2 relation, $F(1,31) = 6.19$, $p = .018$, $\eta_p^2 = .17$.

Mean error percentages are summarized in Table 1 and they substantiate the RT pattern with a close-to-significant interaction, $F(1,31) = 3.67$, $p = .065$, $\eta_p^2 = .11$. The main effect of R2–E2 relation approached significance, $F(1,31) = 3.40$, $p = .075$, $\eta_p^2 = .10$, whereas the main effect of R1–R2 relation was not significant, $F(1,31) = 0.13$, $p = .716$, $\eta_p^2 < .01$.

3.3. Discussion

The results from Experiment 2 are very similar to the pattern observed in Experiment 1. Again, we obtained a standard BCE for the compatible R2–E2 relation, i.e., RT1 was faster when R1 was a left/right key press and R2 and E2 both moved in the left/right direction. The BCE with the incompatible R2–E2 relation was statistically different and numerically even reversed compared to the BCE with compatible response effects. At the same time, the reversed BCE was not significant itself and was less pronounced than the standard BCE. This points to an important contribution of intended action effects for the BCE, but it again leaves room for contributions from other representations.

Furthermore, we observed a reliable influence of R2–E2 relation on R2 with faster responses when hand and lever moved in the same direction (compatible relation) as compared to opposite directions (incompatible relation). This REC effect replicates previous studies on tool-use actions (Janczyk, Pfister & Kunde, 2012; Kunde et al., 2007, 2012) and indicates that selecting and initiating R2 involved anticipations of the consequences (i.e., the lever movement). In turn, these anticipations seem to be driving the BCE as well.

4. Experiment 3

Experiments 1 and 2 have demonstrated the importance of intended action effects in Task 2 and their compatibility with R1 for BCEs. However, in both experiments it was only Task 2 where responses were less important than their visual effects. This might have created asymmetries between the two tasks and perhaps made Task 2 more difficult or attention-demanding. Our aim was therefore to create a more balanced relationship between Task 1 and Task 2 by equipping both R1 and R2 with task-relevant action effects. Action effects in both tasks were two columns that could either grow high or low, as earlier used by Janczyk et al. (2009). The purpose for using these visual effects was twofold: They allowed us to see whether our findings generalize to different kinds of visual effects and to avoid introducing another left/right component to the task—which might have created confusion.

We expected a standard BCE for one group of participants that produced the same effects in both tasks with compatible R1–R2 relations. The critical results relate to another group that produced the same effects with incompatible R1–R2 relations. If only the R1–R2 relation counts, a standard BCE should emerge. However, if – as suggested by Experiments 1 and 2 – the compatibility of action effects is crucial, the BCE should diminish or even reverse for this group. Note also that both tasks should now be of comparable difficulty as both include an explicit, task-relevant R–E relation.

4.1. Method

4.1.1. Participants

Thirty-two undergraduate students (mean age: 23.8 years, SD = 3.5; 24 female) from Würzburg University participated for course credit. All participants were naïve regarding the hypotheses of the experiment.

4.1.2. Apparatus and stimuli

Stimuli, responses, and apparatus were as in Experiment 1 with only few differences. The two circles (the “lights” in Experiment 1) were not shown. Instead, two rectangles (3 x 10 cm; white outline) were shown with their inner, lower corner 10 cm to the left/right and 11.5 cm below screen center. Upon execution of a response, these rectangles were continuously filled similar to growing columns (cf. Janczyk et al., 2009, Exp. 1). The growth stopped either at the top of the rectangles (high growing), or after 2 cm (low growing) for 800 ms and then shrunk again completely (see Fig. 4 for an illustration).

4.1.3. Procedure

Experiment 3 followed Experiment 1 in most procedural aspects. Importantly, however, both tasks had the explicit goal of producing either a low or a high growing column (= E1 and E2) in response to the color (Task 1) or the identity (Task 2) of the stimulus letter.

4.1.4. Design and analyses

Participants completed 12 blocks of 32 trials and the first two blocks were considered practice and excluded from analyses. The stimulus–response mappings in both tasks were counterbalanced across participants, as was the mapping of effects E1 and E2 (low vs. high growing) to S–R combinations. As a consequence, half of the participants produced the same effects (i.e., both E1 and E2 growing high or low) with compatible R1–R2 relations. The other half produced different effects (i.e., one column growing high and the other growing low; see Fig. 4 for an illustration) with compatible R1–R2 relations—thus creating the variable 'E1–E2 relation'.

The data were analyzed by means of a 2 x 2 mixed ANOVA. The variable 'E1–E2 relation' (same vs. different) was manipulated between-subjects and 'R1–R2 relation' (compatible vs. incompatible) was manipulated within-subjects. All trials with wrong response order or without R1 given within 2500 ms were excluded first. Of the remaining trials, 0.9% were excluded as both responses were not separated by at least 50 ms. RT analyses were restricted to trials with two correct responses and outliers were excluded if RTs deviated from the mean of the respective design cell by more than 3 standard deviations (Task 1: 1.27%; Task 2: 1.26%).

4.2. Results

4.2.1. Task 1

Mean RTs for Task 1 are visualized in Fig. 4 (see also Table 2). First, the main effect of R1–R2 relation was not significant, $F(1,30) = 3.43$, $p = .074$, $\eta_p^2 = .10$. The main effect of E1–E2 relation was significant, however, indicating overall slower RTs for the 'different E1–E2 relation' group, $F(1,30) = 5.21$, $p = .030$, $\eta_p^2 = .15$. Most importantly, the interaction was again significant, $F(1,30) = 7.77$, $p = .009$, $\eta_p^2 = .21$. Hence, the pattern of results was as in the previous experiments: A significant standard BCE in the 'same E1–E2 relation' group, $t(15) = 3.19$, $p = .003$, $d = 1.13$, but a numerically reversed, no longer significant BCE in the 'different E1–E2 relation' group, $t(15) = 0.68$, $p = .253$, $d = 0.24$ (one-tailed). The respective 95% confidence intervals (two-tailed) for the pairwise differences were [32 ms; 160 ms] and [−80 ms; 41 ms]. The comparison of the size of the BCEs after reversing the sign for participants in the 'different E1–E2' group showed a larger BCE for the 'same E1–E2' group, $t(30) = 1.85$, $p = .037$, $d = 0.65$ (one-tailed).

Mean error percentages are summarized in Table 2. Participants in the 'same E1–E2' group made slightly more

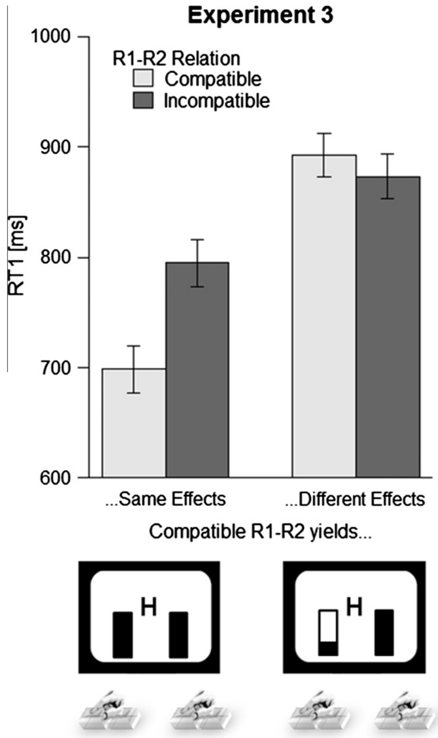

Fig. 4. Mean response times in Task 1 (RT1) of Experiment 3 as a function of R1–R2 relation and E1–E2 relation group. Error bars are within-subjects standard errors, computed separately for each E1–E2 relation group (Pfister & Janczyk, 2013). Visualization of the experimental design is provided at the bottom.

errors, giving rise to a marginally significant main effect of E1–E2 relation, $F(1,30) = 3.70$, $p = .064$, $\eta_p^2 = .11$. Neither the main effect of R1–R2 compatibility, $F(1,30) = 2.22$, $p = .146$, $\eta_p^2 = .07$, nor the interaction, $F(1,30) = 0.06$, $p = .810$, $\eta_p^2 < .01$, were significant.

4.2.2. Task 2

Mean RTs and mean error percentages for Task 2 are summarized in Table 2 and closely mirror those of Task 1. The main effect of R1–R2 relation was not significant, $F(1,30) = 3.49$, $p = .071$, $\eta_p^2 = .10$, but participants in the 'different E1–E2' group responded slower, $F(1,30) = 6.73$, $p = .015$, $\eta_p^2 = .18$. Further, the interaction was significant, $F(1,30) = 9.26$, $p = .005$, $\eta_p^2 = .24$.

Participants in the 'different E1–E2' group made less errors, $F(1,30) = 11.50$, $p = .002$, $\eta_p^2 = .28$, and across both groups, less errors were made with incompatible R1–R2 relations, $F(1,30) = 5.06$, $p = .032$, $\eta_p^2 = .14$. The interaction, in contrast, was not significant, $F(1,30) = 0.87$, $p = .358$, $\eta_p^2 = .03$.

4.3. Discussion

Experiment 3 focused on the relation between E1 and E2. For those participants that produced the same visual effects with spatially compatible motor responses ('same E1–E2' group), a standard BCE was observed, i.e., faster

Table 2
Mean RTs (in ms) and percentages error (PE) from Experiment 3 in Task 1 and 2 as a function of R1–R2 relation and E1–E2 relation group. 'Same E1–E2' means that compatible R1–R2 relations produced the same visual action effects, whereas in the 'different E1–E2' relation they produced different visual action effects. Crosstalk effects were computed by subtracting values from the compatible R1–R2 relation from those in the incompatible R1–R2 relation line-by-line. Crosstalk cannot only go from Task 2 to Task 1 (backward crosstalk effect; BCE), but also from Task 1 to Task 2, and we use the label "forward crosstalk effect" (FCE) for the latter variant.

Experiment 3			R1–R2 Relation		
		E1–E2 Relation	Incompatible	Compatible	BCE/FCE
RT	Task 1	Same	795	699	96
		Different	873	893	-20
	Task 2	Same	986	874	112
		Different	1121	1148	-27
PE	Task 1	Same	3.5	2.8	0.7
		Different	2.1	1.7	0.4
	Task 2	Same	2.7	4.0	-1.3
		Different	1.3	1.9	-0.6

RT1 with a compatible R1–R2 relation. However, the BCE was significantly different and numerically (though again not itself significant and of smaller size compared with the standard BCE) reversed for the other group of participants that produced the same effects with incompatible R1–R2 relations. Thus, in both groups, faster RT1 were observed when the particular R1–R2 combination resulted in the same rather than different effects. As such, the results closely mirror those obtained in Experiments 1 and 2.

Note that participants in the 'different E1–E2' group were overall slower than participants in the 'same E1–E2' group. However, given that the error effect went into the opposite direction, this seems to suggest a slightly different speed-accuracy emphasis in the two groups rather than a systematic difference. In any case, this observation does not affect or undermine our main conclusions.

5. General discussion

To understand the limits of dual-task performance it is important to know which aspects of concurrent actions can be processed in parallel and which cannot. A tool to study this question is the backward crosstalk effect (BCE), the observation that the response in an upcoming Task 2 can influence performance in the temporally preceding Task 1 in a dual-task situation. Arguably, those features of Task 2 responses that are able to engage in crosstalk with those of Task 1 responses, are not subject to serial 'first Task 1, then Task 2' processing. Rather, such features can be processed simultaneously for two or more concurrent tasks. The present study asked whether the activation of features of responses and of intended action effects are suitable for such parallel processing. In the following, we will summarize the results and relate them to our research question, and then discuss what these results imply for theorizing about BCEs and how they constrain existing (dual-task) theories.

5.1. The role of action effects

The first report of a BCE (Hommel, 1998) motivated a departure from classical stage models of information processing and the related response selection bottleneck models of dual-task performance (e.g., Pashler, 1994). Even though the phenomenon of BCEs itself informs theorizing on human action control, previous studies did not yet allow for a mechanistic understanding of the effect. To address this open issue, we focused on R2–R1 compatibility here (see Hommel, 1998; Lien & Proctor, 2000, Exp. 2 and 3). More specifically, we investigated which features are responsible for BCEs: Features of the required manual response itself or features of the effect this response was intended to generate? In Experiment 1 and 2, we coupled the overt responses in Task 2 (R2) with contingent visual effects (E2). When these effects were spatially compatible with R2, a standard BCE occurred, as indicated by R1 facilitation if R2 was compatible. However, and more interesting, this BCE was significantly altered in all experiments (as evident in the significant interactions), and numerically even reversed, when the effects E2 were spatially incompatible with the response R2. In Experiment 3, we coupled both R1 and R2 with visual Es and observed similar results, i.e., a facilitation of Task 1 performance when both Es were the same.

Our findings suggest that BCEs – at least to a considerable degree – depend on feature overlap *between intended action effects* of the concurrent tasks. This fits well with the ideomotor account, which holds that actions are selected in terms of their intended sensory consequences. In broader terms, these findings point to an important influence of *action goals* on dual-task performance, and how these findings call for modifications of existing models will be discussed in the next section.

In general it appears that intended effects indeed contribute to various different interference phenomena (Hommel, 1993; Janczyk, Pfister, Crognale et al., 2012; Janczyk et al., 2009), even for backwards crosstalk in a dual-task situation as studied here. It is important to emphasize that this prominent role of intended action effects was observed in a task in which the correct response was entirely determined by a stimulus. This runs counter to the claim of Herwig, Prinz, and Waszak (2007), who suggested that action effects play a role in freely chosen (i.e., endogenously selected) actions but not in stimulus-driven responses, and adds to the increasing evidence that action effects mediate response selection even with stimulus-driven responses (Hommel, 1993; Kunde, 2001; Pfister, Kiesel, & Hoffmann, 2011; Pfister & Kunde, 2013; Wolfensteller & Ruge, 2011; for recent discussions of differences and commonalities between these two kinds of actions [and their effects on a short-term time scale], see Herwig & Waszak, 2012; Janczyk, Dambacher, Bieleke, & Gollwitzer, 2014, and Janczyk, Heinemann, & Pfister, 2012).

It should also be noted, however, that the observed BCEs were far from being perfectly reversed: Tested individually, the reversed BCEs did not reach statistical significance and, more importantly, the effect sizes were considerably smaller than those for standard BCEs. Furthermore, in Experiment 2 and 3, the reversed BCEs in terms of RTs were of smaller magnitude than the standard BCEs. We thus continue by reporting several analyses that attempt to characterize the "true" effects more closely by taking into account the three experiments simultaneously. First, combining the effect sizes across the three experiments in a meta-analysis (Hedges & Olkin, 1985) yielded $d = 1.11$ and $d = 0.30$ for the standard and the reversed BCE, respectively. Secondly, we combined data from the three experiments and ran separate mixed ANOVAs for the standard and the reversal conditions with R1–R2 relation as a within-subjects variable and experiment as a between-subjects variable, where we formulated a contrast for R1–R2 relation and calculated its confidence interval. Importantly, both ANOVAs yielded non-significant interactions, suggesting sufficient comparability across the experiments despite their methodological differences, $F(2,61) = 1.40$, $p = .255$, $\eta_p^2 = .04$, for the interaction in the standard BCE condition, and $F(2,61) = 0.35$, $p = .709$, $\eta_p^2 = .01$, for the interaction in the reversal condition. The resulting 95% confidence intervals amounted to [47 ms; 98 ms] for the standard BCE and [−62 ms; 3 ms] for the reversed BCE. In addition to the significant interaction observed in each single experiment, these ranges suggest with more confidence than the single experiments that the visual action effects indeed had a pronounced impact on the BCE and dual-task performance with the large majority of values included in the confidence interval for the reversed BCE pointing to a 'real' reversal. Yet, there is still some space for speculations about other sources and the question remains: Why was the reversal never significant (and less strong in effect size than the standard BCE) in each single experiment?

One possibility is that in the reversal conditions, two sub-groups of participants existed: One group of participants coding with regard to the response location, the other group coding with regard to the intended action effect. This would yield a bimodal distribution of BCEs in the reversal condition. We computed the bimodality coefficient (BC; SAS Institute Inc., 1990) and Hartigan's dip test (Hartigan & Hartigan, 1985) and all results clearly point to a unimodal distribution: The BC was 0.32 (a BC < 0.55 suggests a unimodal distribution; cf. Pfister, Schwarz, Janczyk, Dale, & Freeman, 2013) and the dip test yielded $p = .974$ (with the alternative hypothesis holding that data do not stem from a unimodal distribution). Thus, according to these tests, the distribution of the reversed BCEs was clearly not bimodal (see also Freeman & Dale, 2013).

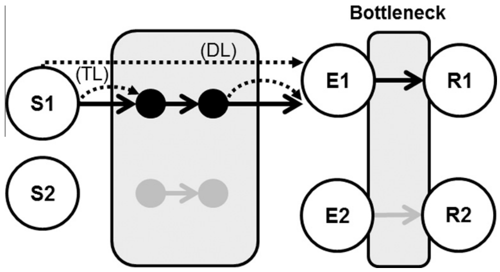

Fig. 5. Schematic illustration of the results from the present study. This schematic is a modified version based on the original suggestion by Hommel (1998; see also Fig. 2). The most important clarification concerns the fact that stimuli do not automatically co-activate representations of overt motor behavior, but rather the associated effects/goals. This automatic process runs in parallel for all tasks and creates BCEs. A subsequent, presumably bottleneck-like, stage gives rise to one possible motor behavior that brings about the desired effects.

Other action features apparently affected performance as well and worked against a complete reversal. Note that, for the incompatible R2–E2 relation, the intended visual effect was incompatible with the location of R1 in the case of a compatible R1–R2 relation. Yet, several other sensory consequences of R2 were still compatible with R1: The proprioceptive feedback from moving the left or right finger, the tactile feedback from touching the left or right key, and the visual and auditory feedback from observing one's movement. It is known that these kinds of feedback are spontaneously and automatically integrated with the cognitive representations of the corresponding action (Hommel, 1996), which suggests that they cannot be ignored altogether. Indeed, systematic manipulations have provided evidence that even goal-irrelevant action features are considered in action selection (Hommel, 1993). According to this line of reasoning, our present findings can be taken to suggest that our participants represented their Task 2 responses in terms of the intended action goal as well as the spatial characteristics of the key, the relative location of the finger, or both. In fact, there is recent evidence that kinesthetic effects do affect performance in much the same way as the visual effects do (Pfister, Janczyk, Gressmann, Fournier, & Kunde, 2014). Thus, in the reversal BCE conditions an incompatibility of kinesthetic and visual effects indeed existed, preventing the visual effects from exerting their influence to the same degree as in the standard BCE conditions. At the same time, however, it appears that participants weighted the intended action goal to such a degree that sufficed to affect the direction of the BCE.[6]

5.2. Theoretical implications and constraints

Only few available models account for BCEs and the standard bottleneck model of dual-task performance

[6] A final hint to explain the smaller reversed than standard BCEs came from an analysis of the IRIs. An ANOVA on IRIs where we considered experiment and BCE condition (standard vs. reversed) as between-subject variables pointed to significantly longer IRIs in the reversed ($M = 314$ ms) than in the standard condition ($M = 280$ ms), $F(1,122) = 4.73$, $p = .031$, $\eta_p^2 = .04$. Likely, weaker BCEs arise the longer the IRI and thus this analysis may provide an important additional hint. At present, however, this analysis is post-hoc and speculative.

(Pashler, 1994) does not belong to them. The common explanation for BCEs involves a distinction between parallel operating response activation and serially operating response selection (for a recent review of possible exceptions to serial response selection, see Janczyk, Pfister, Wallmeier, & Kunde, 2014). Specifically, Hommel (1998) suggested that perceiving a stimulus automatically activates response features during a parallel stage of response activation, which in turn produces BCEs (see also Figs. 1 and 2). The present findings allow for a specification of this idea by suggesting which features of the responses are activated automatically (see Fig. 5): Any stimulus is translated into an associated action effect or goal to be pursued upon perceiving this stimulus (via direct or transient links). Such a goal might consist in pressing a key at a specified location (R) to create a related E. Assuming that both, Task 1 and Task 2 goals/effects are activated concurrently and similar goals/effects can mutually co-activate themselves, BCEs occur that are based on the goal or effect features. Once these effects have been sufficiently activated, a subsequent mechanism secures that one particular motor behavior suited to bring about the highest activated goal/effect state is executed. This mechanism may be considered response selection proper and it might (but need not) operate strictly serially (Hommel, 1998; Lien & Proctor, 2002). Whether the automatic effect activation happens via transient or direct links was not subject of this research. Yet, an additional analysis of the Experiment 2 data (see the Appendix) suggests direct links developing over time. This makes sense, as participants need first to experience which motor behavior is followed by which (visual) effect.

How does this scenario fit with the available literature? Remember that ideomotor theory proposes motor actions to be selected by retrieving to-be-expected sensory action consequences. If so, response selection might be equivalent to the recollection of effect codes (Hommel, 2009). Combined with the traditional assumption that response selection is a capacity-limited, serially operating process (even in the modifications suggested by Hommel, 1998, or Lien & Proctor, 2002; see also Fig. 1b), it follows that the recollection of effect codes should be capacity-limited as well. This assumption was investigated in a series of PRP experiments by Paelecke and Kunde (2007), who utilized the locus-of-slack logic (Schweickert, 1978; for other applications see, e.g., Janczyk, 2013; Kunde et al., 2012) to localize the stage where endogenous action effect activation (i.e., anticipation of upcoming action effects) occurs. Across several experiments, REC effects combined additively with the SOA (stimulus onset asynchrony) manipulation. According to the locus-of-slack logic this indeed points to a bottleneck process. In other words, effect anticipation coincides with capacity-limited response selection. In contrast, when action effects that were previously associated with a response were presented as stimuli (see Elsner & Hommel, 2001), compatibility between these effects/stimuli and the responses combined underadditively with SOA. Paelecke and Kunde suggested that the presentation of action effects as stimuli activates the associated responses during the response activation stage, i.e., in a capacity-unlimited fashion (Hommel, 1998; Lien & Proctor, 2002; see Fig. 1b). In other words, the exogenous activation of action effects can thus proceed in parallel but their endogenous activation cannot. The present finding that effects (or at least features of them) are anticipated and activated in parallel with other processes is at first glance at odds with this latter conclusion.

One interpretation is that any environmental stimuli automatically activate certain features of effects or currently relevant goals. For example, the left-component of R1 automatically activates the left-component of E2 and so on. In such situations (features of) effects then become activated in parallel with other stages. This case bears similarities to those experiments of the Paelecke and Kunde (2007) study, where previously acquired effects were presented as stimuli. If, in contrast, the environment leads to no direct activation of currently relevant effects, endogenous effect activation from scratch is necessary. In this case, the required selection of suited effects may be a serial bottleneck process. Indeed, while in the present study, there was overlap between, e.g., R1 and E2 (obviously a prerequisite to study crosstalk effects like those investigated in Exp. 1 and 2), such overlap did not exist in the study by Paelecke and Kunde. Interpreted this way, the Paelecke and Kunde scenario fits well with our present observations: First, we see that perceiving a stimulus that is associated with a particular response and action effect creates crosstalk (BCEs). This shows that the exogenous activation of action effects does not underlie capacity limitations, just as Paelecke and Kunde have suggested. At the same time, the finding of the standard PRP effect suggests that some aspect of response selection proceeds serially. If we follow Hommel (1998) in considering this serial process the actual endogenous selection process, assuming that response selection operates on action effect representations (Hommel, 2009) would imply that endogenous action effect operations are serial—again, as suggested by Paelecke and Kunde.

Logan and Gordon (2001) extended the Theory of Visual Attention (TVA) to dual-task situations (Executive Control of TVA; ECTVA) to account for BCEs. According to their model, stimuli are constantly categorized and available evidence for a specific response is accumulated. Once a critical difference between possible responses of one task is reached, the response with the strongest support will be executed. BCEs occur because the Task 2 stimulus is categorized while Task 1 is processed and thus contributes to "selection" of the proper response in Task 1. Although ECTVA has good explanatory power for various phenomena in dual-task situations including BCEs, it does not incorporate events that occur after the response is given, i.e., action effects. To accommodate the present findings, an additional process must be assumed that relates the stimulus to the effect that will be produced by the correct response, and categorization must then be based on these effect representations or – in broader terms – the actual action goals, but not on the stimulus per se (see Thomson, Watter, & Finkelshtein, 2010, for related ideas).

6. Conclusions

The present study aimed at investigating what features of responses can become activated automatically in dual-task situations. To address this question, we investigated the role of intended action effects, i.e., action goals, for backward crosstalk effects (BCEs). Our findings attribute to them an important role in determining the direction of BCEs. It is thus not so much the features of the overt response that are activated in parallel with other processes, but rather the anticipated and intended consequences of the action, i.e., the action goals. Such outcome is in line with the assumption of ideomotor theory that actions are represented and selected via their sensory consequences. In sum, our results demonstrate that basic mechanisms that operate in human action control are also able to explain the interplay between multiple actions and tasks. The results may also be taken to indicate that remote action goals have to be considered for optimizing dual-task performance.

Acknowledgments

We thank Eric Ruthruff and Iring Koch for valueable comments and suggestions on a previous version of this manuscript. Parts of this research were supported by the Deutsche Forschungsgemeinschaft (DFG; German Research Council), project KU 1964/2-2.

Appendix A. Direct- or transient-links?

Hommel (1998) discussed two possible mechanisms that might underlie the automatic translation from stimulus to response features. The *transient-link model* assumes that stimulus–response (S–R) rules are lingering in working memory and, once identified, stimuli automatically activate the respective response via these rules. According to the *direct-link model*, direct and permanent links from a stimulus to a response are established with increasing practice, leading to direct response activation without resorting to S–R rules stored in working memory. These models were tested more thoroughly by Hommel and Eglau (2002), who found BCEs to be independent of working memory load. These results were interpreted in favor of direct links. Other authors, however, found a dependence on working memory load and preferred the transient-link model for that reason (Ellenbogen & Meiran, 2008).

Our experiments were not designed to directly address this issue. In Experiment 2, however, all participants performed in the compatible R2–E2 condition, which allowed us to perform an exploratory time course analysis for this condition. According to the transient-link model, a BCE should be evident from the very beginning of an experiment, as the mere instruction of the rules is sufficient for automatic activation tendencies (for converging evidence from flanker tasks, see also Cohen-Kdoshay & Meiran, 2007, 2009).

A.1. Exploratory time course analysis

We analyzed data from the compatible R2–E2 condition of Experiment 2 ($n = 32$) as a function of block, including the two practice blocks (see Fig. A1). The corresponding 2 (R1–R2 relation) x 10 (block) within-subjects ANOVA first yielded a significant effect of block, $F(9,279) = 5.45$, $p < .001$, $\eta_p^2 = .15$ (Greenhouse–Geisser adjusted), suggesting a slight decrease in RTs across blocks. The main effect of R1–R2 compatibility was also significant, $F(1,31) = 26.70$, $p < .001$, $\eta_p^2 = .46$, as was the interaction, $F(9,279) = 1.98$, $p = .041$, $\eta_p^2 = .06$. Separate one-tailed *t*-tests within each block showed that a BCE was present in all blocks (all $ps \leqslant .006$), except for the first one, $t(31) = 1.24$, $p = .112$.

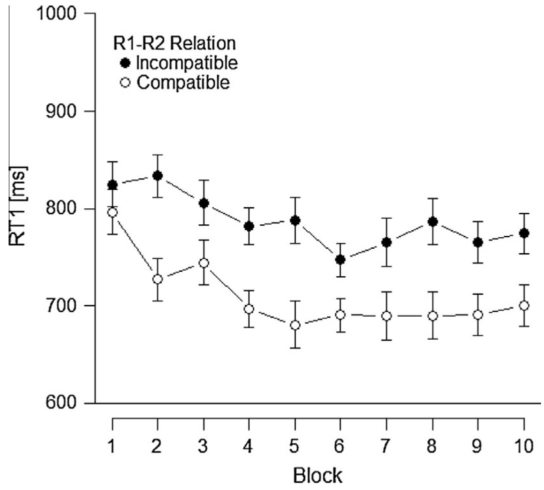

Fig. A1. Mean response times of Task 1 (RT1) from the compatible R2–E2 relation condition of Experiment 2 as a function of R1–R2 relation and block number. Error bars are within-subject standard errors, computed separately for each block (Pfister & Janczyk, 2013).

These results suggest that the BCE developed over time and was absent at the very beginning of the experiment. This outcome is thus in line with a type of the direct-link model, where in the course of the experiment direct, long-term links between the stimuli and the corresponding effect features are established. Still, it cannot be excluded that both transient- and direct-links coexist and contribute to BCEs, perhaps depending on the number of S–R rules (Ellenbogen & Meiran, 2008).

References

Badets, A., Koch, I., & Toussaint, L. (2013). Role of an ideomotor mechanism in number processing. *Experimental Psychology, 60*, 34–43.
Cohen, L. (1971). Synchronous bimanual movements performed by homologous and non-homologous muscles. *Perceptual and Motor Skills, 32*, 639–644.
Cohen-Kdoshay, O., & Meiran, N. (2007). The representation of instructions in working memory leads to autonomous response activation: Evidence from the first trials in the flanker paradigm. *The Quarterly Journal of Experimental Psychology, 60*, 1140–1154.
Cohen-Kdoshay, O., & Meiran, N. (2009). The representation of instructions operates like a prepared reflex: Flanker compatibility effects found in first trial following S-R instructions. *Experimental Psychology, 56*, 128–133.
Ellenbogen, R., & Meiran, N. (2008). Working memory involvement in dual-task performance: Evidence from the backward compatibility effect. *Memory & Cognition, 36*, 968–978.
Ellenbogen, R., & Meiran, N. (2011). Objects and events as determinants of parallel processing in dual tasks: Evidence from the backward compatibility effect. *Journal of Experimental Psychology: Human Perception and Performance, 37*, 152–167.
Elsner, B., & Hommel, B. (2001). Effect anticipation and action control. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 229–240.
Freeman, J. B., & Dale, R. (2013). Assessing bimodality to detect the presence of a dual cognitive process. *Behavior Research Methods, 45*, 83–97.

Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: With special reference to the ideo-motor mechanism. *Psychological Review, 77*, 77–99.
Hartigan, J. A., & Hartigan, P. M. (1985). The dip test of unimodality. *The Annals of Statistics, 13*, 70–84.
Hedges, L. V., & Olkin, I. (1985). *Statistical methods for meta-analysis*. Orlando, FL: Academic Press.
Herwig, A., Prinz, W., & Waszak, F. (2007). Two modes of sensorimotor integration in intention-based and stimulus-based actions. *The Quarterly Journal of Experimental Psychology, 60*, 1540–1554.
Herwig, A., & Waszak, F. (2012). Action-effect bindings and ideomotor learning in intention- and stimulus-based actions. *Frontiers in Psychology, 3*, 444.
Heuer, H. (1993). Structural constraints on bimanual movements. *Psychological Research, 55*, 83–98.
Hommel, B. (1993). Inverting the Simon effect by intention. *Psychological Research, 55*, 270–279.
Hommel, B. (1996). The cognitive representation of action: Automatic integration of perceived action effects. *Psychological Research, 59*, 176–186.
Hommel, B. (1998). Automatic stimulus–response translation in dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 1368–1384.
Hommel, B. (2009). Action control according to TEC (theory of event coding). *Psychological Research, 73*, 512–526.
Hommel, B., & Eglau, B. (2002). Control of stimulus–response translation in dual-task performance. *Psychological Research, 66*, 260–273.
Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding: A framework for perception and action. *Behavioral and Brain Sciences, 24*, 849–878.
James, W. (1890). *The principles of psychology (orig. 1890)*. Cambridge, MA: Harvard University Press.
Janczyk, M. (2013). Level-2 perspective taking entails two processes: Evidence from PRP experiments. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 39*, 1878–1887.
Janczyk, M., Dambacher, M., Bieleke, M., & Gollwitzer, P. M. (2014). The benefit of no choice: Goal-directed plans enhance perceptual processing. *Psychological Research*. http://dx.doi.org/10.1007/s00426-014-0549-5.
Janczyk, M., Heinemann, A., & Pfister, R. (2012). Instant attraction: Immediate action-effect bindings occur for both, stimulus- and goal-driven actions. *Frontiers in Psychology, 3*, 446.
Janczyk, M., Pfister, R., Crognale, M., & Kunde, W. (2012). Effective rotations: Action effects determine the interplay of mental and manual rotations. *Journal of Experimental Psychology: General, 141*, 489–501.
Janczyk, M., Pfister, R., & Kunde, W. (2012). On the persistence of tool-based compatibility effects. *Journal of Psychology, 220*, 16–22.
Janczyk, M., Pfister, R., Wallmeier, G., & Kunde, W. (2014). Exceptions to the PRP Effect? A comparison of prepared and unconditioned reflexes. *Journal of Experimental Psychology. Learning, Memory, and Cognition*. http://dx.doi.org/10.1037/a0035548.
Janczyk, M., Skirde, S., Weigelt, M., & Kunde, W. (2009). Visual and tactile action effects determine bimanual coordination performance. *Human Movement Science, 28*, 437–449.
Koch, I., & Kunde, W. (2002). Verbal response-effect compatibility. *Memory & Cognition, 30*(8), 1297–1303.
Kunde, W. (2001). Response-effect compatibility in manual choice reaction tasks. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 387–394.
Kunde, W., Hoffmann, J., & Zellmann, P. (2002). The impact of anticipated action effects on action planning. *Acta Psychologica, 109*, 137–155.
Kunde, W., Krauss, H., & Weigelt, M. (2009). Goal congruency without stimulus congruency in bimanual coordination. *Psychological Research, 73*, 34–42.
Kunde, W., Müsseler, J., & Heuer, H. (2007). Spatial compatibility effects with tool use. *Human Factors, 49*, 661–670.
Kunde, W., Pfister, R., & Janczyk, M. (2012). The locus of tool-transformation costs. *Journal of Experimental Psychology: Human Perception and Performance, 38*, 703–714.
Kunde, W., & Weigelt, M. (2005). Goal congruency in bimanual object manipulation. *Journal of Experimental Psychology: Human Perception and Performance, 31*, 145–156.
Lien, M.-C., & Proctor, R. W. (2000). Multiple spatial correspondence effects on dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 26*, 1260–1280.
Lien, M.-C., & Proctor, R. W. (2002). Stimulus–response compatibility and psychological refractory period effects: Implications for response selection. *Psychonomic Bulletin & Review, 9*, 212–238.
Logan, G. D., & Delheimer, J. A. (2001). Parallel retrieval in dual-task situations: II. Episodic memory. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 27*, 668–685.
Logan, G. D., & Gordon, R. D. (2001). Executive control of visual attention in dual-task situations. *Psychological Review, 108*, 393–434.
Logan, G. D., & Schulkind, M. D. (2000). Parallel retrieval in dual-task situations: I. Semantic memory. *Journal of Experimental Psychology: Human Perception and Performance, 26*, 1072–1090.
Mechsner, F., Kerzel, D., Knoblich, G., & Prinz, W. (2001). Perceptual basis of bimanual coordination. *Nature, 414*, 69–73.
Memelink, J., & Hommel, B. (2013). Intentional weighting: A basic principle in cognitive control. *Psychological Research, 77*, 249–259.
Miller, J. (2006). Backward crosstalk effects in psychological refractory period paradigms: Effects of second-task response type on first-task response latencies. *Psychological Research, 70*, 484–493.
Miller, J., & Alderton, M. (2006). Backward response-level crosstalk in the psychological refractory period paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 37*, 149–165.
Navon, D., & Miller, J. (1987). Role of outcome conflict in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance, 13*, 435–448.
Paelecke, M., & Kunde, W. (2007). Action-effect codes in and before the central bottleneck: Evidence from the PRP paradigm. *Journal of Experimental Psychology: Human Perception and Performance, 33*, 627–644.
Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin, 116*, 220–244.
Pashler, H., & Johnston, J. C. (1989). Chronometric evidence for central postponement in temporally overlapping tasks. *Quarterly Journal of Experimental Psychology, 41A*, 19–45.
Pfister, R., & Janczyk, M. (2012). Harleß' apparatus of will: 150 years later. *Psychological Research, 76*, 561–565.
Pfister, R., & Janczyk, M. (2013). Confidence intervals for two sample means: Calculation, interpretation, and a few simple rules. *Advances in Cognitive Psychology, 9*, 74–80.
Pfister, R., Janczyk, M., Gressmann, M., Fournier, L. R., & Kunde, W. (2013). Good vibrations? Vibrotactile self-stimulation reveals anticipation of body-related action effects in motor control. *Experimental Brain Research, 232*, 847–854.
Pfister, R., Kiesel, A., & Hoffmann, J. (2011). Learning at any rate: Action-effect learning for stimulus-based actions. *Psychological Research, 75*, 61–65.
Pfister, R., Kiesel, A., & Melcher, T. (2010). Adaptive control of ideomotor effect anticipations. *Acta Psychologica, 135*, 316–322.
Pfister, R., & Kunde, W. (2013). Dissecting the response in response-effect compatibility. *Experimental Brain Research, 224*(4), 647–655.
Pfister, R., Schwarz, K. A., Janczyk, M., Dale, R., & Freeman, J. B. (2013). Good things peak in pairs: A note on the bimodality coefficient. *Frontiers in Quantitative Psychology and Measurement, 4*, 700. http://dx.doi.org/10.3389/fpsyg.2013.00700.
SAS Institute Inc. (1990). *SAS/STAT user's guide, Version 6* (4th ed.). Cary, NC: Author.
Schweickert, R. (1978). A critical path generalization of the additive factor method: Analysis of a Stroop task. *Journal of Mathematical Psychology, 18*, 105–139.
Schubert, T., Fischer, R., & Stelzel, C. (2008). Response activation in overlapping tasks and the response-selection bottleneck. *Journal of Experimental Psychology: Human Perception and Performance, 34*, 376–397.
Stenneken, P., Aschersleben, G., Cole, J., & Prinz, W. (2002). Self-induced versus reactive triggering of synchronous movements in a deafferented patient and control subjects. *Psychological Research, 66*, 40–49.
Stock, A., & Stock, C. (2004). A short history of ideo-motor action. *Psychological Research, 68*, 176–188.
Thomson, S. J., Watter, S., & Finkelshtein, A. (2010). Parallel response selection in dual-task situations via automatic category-to-response translation. *Attention, Perception, & Psychophysics, 72*, 1791–1802.
Tombu, M., & Jolicoeur, P. (2003). A central capacity sharing model of dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 3–18.
Wallace, R. J. (1971). S-R compatibility and the idea of a response code. *Journal of Experimental Psychology, 88*, 354–360.
Welford, A. T. (1952). The "psychological refractory period" and the timing of high-speed performance: A review and a theory. *British Journal of Psychology, 43*, 2–19.
Wexler, M., Kosslyn, S. M., & Berthoz, A. (1998). Motor processes in mental rotation. *Cognition, 68*, 77–94.
Wohlschläger, A., & Wohlschläger, A. (1998). Mental and manual rotations. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 397–412.
Wolfensteller, U., & Ruge, H. (2011). On the timescale of stimulus-based action-effect learning. *The Quarterly Journal of Experimental Psychology, 64*, 1273–1289.