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Dissociating action-effect activation and effect-based response selection☆

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ABSTRACT

Anticipated action effects have been shown to govern action selection and initiation, as described in ideomotor theory, and they have also been demonstrated to determine crosstalk between different tasks in multitasking studies. Such effect-based crosstalk was observed not only in a forward manner (with a first task influencing performance in a following second task) but also in a backward manner (the second task influencing the preceding first task), suggesting that action effect codes can become activated prior to a capacity-limited processing stage often denoted as response selection. The process of effect-based response production, by contrast, has been proposed to be capacity-limited. These observations jointly suggest that effect code activation can occur independently of effect-based response production, though this theoretical implication has not been tested directly at present. We tested this hypothesis by employing a dual-task set-up in which we manipulated the ease of effect-based response production (via response-effect compatibility) in an experimental design that allows for observing forward and backward crosstalk. We observed robust crosstalk effects and response-effect compatibility effects alike, but no interaction between both effects. These results indicate that effect activation can occur in parallel for several tasks, independently of effect-based response production, which is confined to one task at a time.

1. Introduction

Performing multiple tasks at once is difficult for human beings and readily leads to performance impairments. The reason behind such performance decrements is often attributed to a serial processing stage that creates a bottleneck in human information processing that can only be occupied by one operation at a time (Pashler, 1994; Welford, 1952). Previous studies have identified the performance bottleneck as *response selection* (McCann & Johnston, 1992; Pashler & Johnston, 1989). That is: Whereas other processing stages can seemingly be carried out in parallel for different tasks, response selection seems restricted to serial processing of one task after the other.

However, evidence of so-called *backward crosstalk* challenges the concept of strictly serial processing (Hommel, 1998; Lien & Proctor, 2002; Miller, 2006). Crosstalk emerges if two tasks, supposed to be carried out at the same time or in very short succession, share certain features (such as requiring a “left” response). Crosstalk manifests as facilitation or interference effects if these features are (spatially) compatible or incompatible, respectively. That is, participants respond faster when the responses for two tasks are compatible than when they are incompatible (see also Way & Gottsdanker, 1968, for an early demonstration of between-task correspondence effects). Crosstalk can affect both tasks at hand and it is termed *forward*, if the first task affects the performance of the second task, whereas it is termed *backward*, if the second task affects the performance of the first task. The observation of backward crosstalk is especially relevant because strictly serial processing of both tasks would not allow for such backward crosstalk to take place, as relevant response features would only be retrieved during response selection. An adjustment of the bottleneck model therefore assumes an additional stage of *response activation* to take place before response selection, with possible crosstalk between tasks happening during this stage.

Direct evidence for the concept of response activation as a parallel rather than serial process has been observed with response-priming setups (Schubert, Fischer, & Stelzel, 2008). Participants in this study worked on a psychological refractory period (PRP) task that is commonly used to probe for response selection bottlenecks. PRP designs typically consist of two tasks (e.g., McCann & Johnston, 1992; Miller & Reynolds, 2003; Pashler, 1994; Pashler & Johnston, 1989). These tasks either have to be executed at (almost) the same time or with a considerable delay between tasks. The rationale behind this design lies in the assumption that interference due to multi-tasking should occur only

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in situations in which task timing demands for parallel processing of both tasks – a demand which cannot be met in capacity-limited stages (i.e., *response selection*). Such timing demands occur when both tasks are presented at the same time or in very short succession (i.e., with short stimulus onset asynchronies, SOAs). In these instances, performance of at least one of both tasks should take considerably longer than in conditions with less demanding timing, i.e., when participants have ample time to execute either task (or at least to execute the capacity-limited stages) one after the other (long SOA). In order to test the idea of response activation in pre-bottleneck stages, Schubert and colleagues presented a subliminal prime – a masked arrow stimulus – before stimulus onset in the second task. Subliminally presented arrow stimuli have been shown to exert robust priming effects by activating spatially corresponding responses (e.g., Eimer, 1999). If response activation were restricted to bottleneck stages of information processing, no such priming effects would be expected to arise in bottleneck stages. Schubert and colleagues, however, observed robust priming effects, indicating that response activation does indeed occur in pre-bottleneck stages (for corresponding theoretical perspectives, see Lien & Proctor, 2002; Schubert, 2008).[2]

But what exactly are the features that are activated during response activation and that determine compatibility of two actions? Because actions are assumed to be represented in terms of their perceptible effects (ideomotor theory; Greenwald, 1970; Hommel, 2009; Hommel, Müsseler, Aschersleben, & Prinz, 2001), crosstalk might be expected to emerge based on the compatibility of the to-be-produced action effects, and this is precisely what has been reported (Eder, Pfister, Dignath, & Hommel, 2017; Janczyk, Pfister, Hommel, & Kunde, 2014). In other words: performing multiple actions at once is more effective when action effects of both tasks are compatible (cf. also Janczyk, Skirde, Weigelt, & Kunde, 2009).

Studies on effect-based crosstalk typically combined experimental designs that allow for testing bottleneck models – such as the PRP paradigm – with experimental designs that allow for measuring the impact of anticipated action effects – such as the response-effect (R-E) compatibility paradigm. In the R-E compatibility paradigm, the participants' responses produce action effects such as visual or auditory events that are predictably coupled to each motor response. Responses and their effects vary on a shared dimension to allow for compatible and incompatible R-E mappings, such as a right key response leading to an action effect on the right side of a computer screen (compatible) versus on the left side of the screen (incompatible; e.g., Ansorge, 2002; Chen & Proctor, 2013; Janczyk, Yamaguchi, Proctor, & Pfister, 2015; Kunde, 2001; Pfister, Kiesel, & Melcher, 2010; Pfister & Kunde, 2013; for the concept of dimensional overlap, see Kornblum, Hasbroucq, & Osman, 1990). When participants' responses (spatially) match the subsequent action effects, i.e., when response and effect are spatially compatible, they respond faster than when response and effect do not match. That is, although the respective action effects are not present at the time of the participants' response, they affect the participants' actions. Consequently, the impact of R-E compatibility on action production can only be explained in terms of action effect *anticipations*.[3]

As action effects are important for any singular action, it seems reasonable to assume that they may also play a role when two or more actions are performed at the same time. Indeed, recent studies have investigated the role of effect anticipations in multi-tasking, attempting to reconcile this basic principle of action control with the task processing framework outlined in the multi-tasking literature. Current interpretations of the reported evidence localize effect anticipations within the capacity-limited central bottleneck, i.e., the response selection (Kunde, Pfister, & Janczyk, 2012; Paelecke & Kunde, 2007; Wirth, Pfister, Janczyk, & Kunde, 2015).[4] Crosstalk, by contrast, is supposed to take place during response activation, a stage that can still be performed in parallel for multiple tasks (Eder et al., 2017; Hommel, 1998; Janczyk et al., 2014). In other words, theory suggests that during response activation, the expected action effects of two or more actions can be represented and activated at the same time, yielding compatibility influences between different tasks coined as crosstalk, whereas compatibility influences related to a task's response and its effect (also requiring action effect representation) takes place in a separate, capacity-limited step (for possible reasons discussed later). If this is true, crosstalk on the one hand, and R-E compatibility effects on the other hand should arise in separate stages and should therefore be independent from each other (McClelland, 1979; Sternberg, 1969).

At first sight, the localization of crosstalk and R-E compatibility effects in distinct processing stages might be assumed to reflect that crosstalk is based purely on anticipated effects (what could be labelled "E-E correspondence") whereas R-E compatibility involves response and effect alike. This is not the case, however. Rather, the technical notation of "R-E" conceals that response-effect relations describe relations between body-related effects (e.g., a hand moving to the left or right) and an additional external, environment-related effect (e.g., a lever moving to the left or right). However, actions can be represented and addressed by any type of effect – be it a visual event in the agent's surroundings or a proprioceptive change resulting from the moving body –, and agents have considerable flexibility regarding which representation to use (Hommel, 1993; Hommel, 2009; Memelink & Hommel, 2005). Because any action may be represented in terms of body-related effects or also in terms of additional environment-related effects (Pfister, Janczyk, Gressmann, Fournier, & Kunde, 2014; Wirth, Pfister, Brandes, & Kunde, 2016), R-E compatibility effects, too, reflect costs that arise due to different effect representations (see Pfister & Kunde, 2013, for a related discussion). Effect-based crosstalk and R-E compatibility effects are thus based on the same types of representations. What likely differs between both effects, however, is that crosstalk is mainly based on activation of intended, task-relevant effects alone – irrespective of whether these intended effects relate to the body, the environment, or both –, whereas R-E compatibility also draws on additional effects that are not directly relevant to the goal at hand. Because most actions will typically aim at producing effects in the outside world, the dissociation between task-relevant and task-irrelevant effects will at times correspond to a distinction between (certain) environment-related effects and body-related effects. This correspondence is merely coincidental though and not a theoretical necessity. In any case, the notion that backward crosstalk and R-E compatibility both draw on effect codes that represent a certain action opens up the possibility that both processes might interact. However, as outlined above, previous findings in the literature suggest that both processes pertain to independent stages of information processing.

[2] A boundary condition for parallel activation of response codes is that the experimental setup must allow for crosstalk between both tasks, in terms of overlapping stimulus and/or response sets (Schubert et al., 2008; for related evidence, see also Ellenbogen & Meiran, 2011; Koch, 2009). The model of Schubert et al. further includes a resetting mechanism that annuls accumulated response activation during the slack time after a response has been identified for the first task. We will come back to this issue in the discussion.

[3] Note that effect-based theories of human action control do not claim that action selection, planning, and initiation necessarily involve environment-related effects such as visible or audible effects of own movements. Even though environment-related effects may dominate at times (e.g., Mechsner, Kerzel, Knoblich, & Prinz, 2001), action control can also take advantage of body-related action effects such as proprioceptive or kinesthetic effects that are intimately coupled to each movement (Pfister, Janczyk, Gressmann, et al., 2014; Wirth et al., 2016). From an ideomotor perspective, the operational description of "response-effect" compatibility thus actually reflects "effect-effect" compatibility between body-related and environment-related effects as we will describe later in the introduction (Pfister & Kunde, 2013).

[4] We follow the terminology of Hommel (1998) by distinguishing (parallel) response activation from (serial) response selection proper. The latter stage can also be found under the labels of response verification (Kornblum et al., 1990) or response identification (Schubert et al., 2008) in the literature.

In this study, we aimed at testing this exact question: are crosstalk effects and R-E compatibility effects really independent, despite both relying on activated effect representations, or can crosstalk and effect-based response selection affect one another? To this end, we employed a dual-tasking set-up with the first task requiring participants to operate a controller with the right hand. Hand movements were translated compatibly or incompatibly to a virtual lever movement on a computer screen (e.g., moving the controller to the right could in turn move the lever's tip to the right in the compatible condition or it could move the lever's tip to the left in the incompatible condition), and the second task requiring a left or right key response with the left hand. The first task therefore incorporated R-E compatibility effects, with the response (movement of the controller) matching the action effects (movement of the lever on the screen) or not. We did not introduce any additional visual or auditory action effects for the second task to keep the design as compact as possible. Thus, the action effects of the second task were comprised only of the body-related feedback involved in executing the action and this feedback could either be compatible or incompatible to the task-relevant action effects of the first task (see above for the distinction of body-related and environment-related effects). As crosstalk should only occur when two tasks are to be executed at the same time or in very short succession, we additionally manipulated the time participants were given in-between tasks: in one condition, both tasks were presented at the same time (SOA = 0 ms) and in the second condition, there was a one-second delay between both tasks (SOA = 1000 ms) which should dramatically reduce any possible crosstalk effects, and any effect of Task 1 on Task 2 in general.

In addition to an expected R-E compatibility effect in the first task, we predicted backward and forward crosstalk to occur at least for the short SOA, manifesting in shorter reaction times (RTs) in the first and second task when action effects of both tasks were compatible relative to when they were incompatible. We further hypothesized for these effects to be independent from R-E compatibility effects, that is, there should be no interaction between crosstalk and R-E compatibility within the first task.

2. Methods

2.1. Participants

We recruited 42 participants (mean age 26.2 years ± 0.8 SE_M; 29 female; 39 right-handed). A power analysis suggested a study sample of at least 34 participants to obtain a power of 80% for a medium effect size of $d = 0.50$. Assuming a medium effect size is supported by the literature for all relevant effects that have been studied in prior work. For instance, Experiment 2 of Janczyk et al. (2014) used a similar setup as the present one, with the only exception that the R-E compatibility task (the same lever as in the present experiment) was used as Task 2 rather than Task 1. This experiment reported an effect size of Cohen's $d_Z = 0.54$ for the backward crosstalk effect, and $d_Z = 0.57$ for its effect-based modulation. R-E compatibility effects for the lever apparatus when using this apparatus in Task 1 have further been shown to be large and robust (e.g., $d_Z = 0.81$ in Experiment 3 of Kunde et al., 2012). Based on these previous studies we calculated a possible drop-out rate of 10 to 20% (an additional 4 to 7 participants). Because the interaction of effect-based crosstalk and R-E compatibility has not been studied before, we similarly assume a generic medium-sized effect. All participants received payment or course credit as compensation and gave written informed consent prior to participation.

2.2. Apparatus

Participants operated a custom-built controller with the index finger of their right hand and three external response keys with the index finger of their left hand. The response keys were comprised of the numbers 1 (left key), 2 (central key), and 3 (right key) of a standard keyboard number pad, located next to the participants' left hand for easy access. As in previous experiments (Kunde et al., 2012), the controller consisted of a pen touching the surface of a graphics tablet. The pen was mounted on a bar and could be moved horizontally alongside this bar for about 10 cm. The controller was placed in front of the computer monitor (17″) and controller movements were directly translated into movements of a virtual lever on the computer screen (see Fig. 1). In the R-E compatible condition, the controller was connected to the upper part of the lever so that controller movements made the lever move in the same direction as the operating hand. In the R-E incompatible condition, the controller was connected to the lower part of the lever so that controller movements made the lever move in the opposite direction as the operating hand. The connection of lever and controller was visualized in terms of a grey line either from the lever's tip or from the lever's lower end to the bottom edge of the screen, and therefore to the position of the controller.

2.3. Procedure

Participants performed two tasks in each trial. The first task required the participants to move the upper end of the lever either to the left or to the right in response to the identity of a central letter stimulus, whereas the second task required a left or right keypress response.

The exact sequence of events was as follows (Fig. 1): At the beginning of a trial, participants were prompted to press the central key and keep this key depressed. The prompt consisted of written instructions (“Bitte Starttaste drücken!”; Eng.: “Please press the home key!”) that were displayed in white font against black background. Pressing the central key terminated the prompt and made a horizontal row of three white X appear 4 cm above the upper end of the pointer with an inter-stimulus distance of 6 cm. Participants were to move the lever in central position (pointing directly upwards) and remain within an angle of ± 3° around this central position for a dwell time of 500 ms. Thus the display was the same in either condition before the participants responded.

Then, a warning click (2000 Hz, 50 ms) signaled the upcoming stimulus for Task 1 (S1) which appeared after 1000 ms: The central X changed to either H or S and the letter identity prompted a left or right movement of the lever, and this letter remained visible until completion of the trial. This required either a compatible or incompatible movement of the controller. R-E compatibility was blocked with either the first half of the experiment featuring the compatible or the incompatible condition. Letter-response mapping and order of the compatibility conditions in Task 1 were counterbalanced across participants. Task 2 was signaled by the color of the central letter, which turned either red or green, and S2 was displayed either immediately with S1 or after 1000 ms (i.e., SOA was either 0 ms or 1000 ms). S2 prompted the participants to release the home key with their left hand and press either the left or right key. Color-response mapping of Task 2 was counterbalanced across participants. Note that response and effect in Task 2 are entangled with the response being the keypress itself and the effect being the (spatially compatible) sensory feedback during the keypress.

Participants were instructed to respond as quickly and as accurately as possible, first to the letter identity and then to its color. Reaction time for Task 1 (RT1) was measured when the controller had moved more than 9° (about 1 cm horizontal distance) in either direction, and response completion was registered as soon the lever pointed to either the left or the right X (with a tolerance of 9°). Reaction time for Task 2 (RT2) was measured when the home key was released, and response completion was registered as soon as either key was pressed afterward.[5]

[5] We chose to measure RT for the first task already with movement onset (rather than registering the total time, i.e., initiation time + movement time) for three reasons. First, because the controller only allowed for either left or right movements, the type of

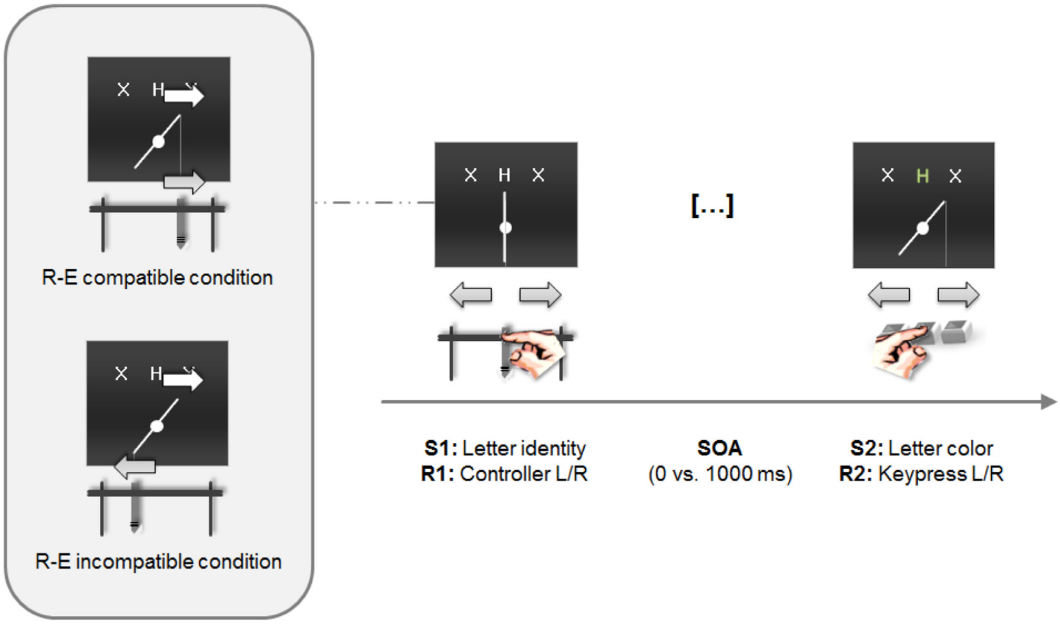

Fig. 1. Design and procedure. Participants performed two tasks in each trial: A horizontal controller movement with their right hand (Task 1) and a left/right keypress response with their left hand (Task 2). Stimuli were colored letters with letter identity (S1) specifying the controller movement (R1) and letter color (S2) specifying the keypress response (R2). Controller movements in Task 1 were continuously translated into movements of a virtual lever on screen that could either move in the same (compatible) direction or in the opposite (incompatible) direction than the operating hand. The *effect relation* of both tasks could therefore be compatible or incompatible on each trial (left/right lever movement on the screen and left/right keypress), and the *response-effect (R-E) relation* of the first task could be either compatible or incompatible. Note that response and effect in the second task are tightly coupled with the response being the keypress and the effect being the sensory feedback during the keypress. Tasks were signaled either simultaneously or with a stimulus-onset asynchrony (SOA) of 1000 ms to manipulate processing overlap.

In case of correct trials, the computer program waited for both responses and the next trial followed after an inter-trial interval of 1500 ms. In case of response anticipations (i.e., responses before stimulus onset) or incorrect responses, participants were provided with feedback that was displayed separately for both responses.

After instructions and initial demonstrations of the R-E compatibility conditions and 8 full demonstration trials, participants performed 10 blocks per R-E compatibility condition. Each block featured 24 trials, consisting of 3 repetitions of all combinations of the factors SOA (0 vs. 1000), R1 (left vs. right) and R2 (left vs. right). Participants were allowed self-paced breaks in between blocks.

2.4. Design and analyses

The design comprised three within-subjects factors: E1-E2 relation (compatible vs. incompatible), SOA (0 vs. 1000), and R1-E1 relation (compatible vs. incompatible). A compatible E1-E2 relation indicated corresponding task-relevant effects in both tasks, e.g., a left movement of the lever's tip on the screen for Task 1 and a response with the left key in Task 2, whereas an incompatible E1-E2 relation indicated non-corresponding task-relevant feedback, e.g., a left movement of the lever's tip on the screen for Task 1 and a response with the right key in Task 2 (note that response and effect coincide for Task 2; we will come back to this issue in the Discussion). The E1-E2 relation was analyzed to test for crosstalk effects in the first (backward crosstalk) or in the second task (forward crosstalk). E1-E2 relation and SOA were varied trial-wise, R1-E1 relation was manipulated block-wise. A compatible R1-E1 relation constituted of corresponding movements of response and effect in Task 1, e.g., a left movement of the controller (operated by the right hand) and a left movement of the lever's tip on the screen, whereas an incompatible R1-E1 relation constituted of non-corresponding movements of response and effect in Task 1, e.g., a left movement of the controller and a right movement of the lever's tip on the screen.

Prior to statistical analysis of both, RT and error data, we excluded post-error trials and the first trial of each block (8.4%) to compensate for post-error and orienting effects. We also excluded trials if the second task was performed before the first task (0.9%) or when it was performed less than 100 ms after the first task was started (1.2%). For RT analyses, we further excluded trials with errors in either task of the current trial (10.8%). RTs of the remaining trials were screened for outliers, with outliers being defined as RTs lying outside 2.5 standard deviations from the RT mean, calculated separately for each cell (i.e., for each possible combination of experimental conditions). Participants were excluded if less than 20 trials remained in any cell to ensure enough data points for reliable statistical analysis; five participants had to be excluded because of this criterion.

RTs and percentage of errors (PEs) were analyzed by means of $2 \times 2 \times 2$ repeated measure analyses of variance (ANOVAs; factors: R1-E1 Relation, compatible vs. incompatible; E1-E2 Relation, compatible vs. incompatible; SOA, 0 ms vs. 1000 ms). Significant interactions were followed-up by simple effects analyses.

(*footnote continued*)
response was already known at this point. Second, a previous study that used this setup in a PRP design found no reliable influences of relevant experimental manipulation on movement times, suggesting that responses were pre-programmed before movement onset to a considerable degree (Kunde et al., 2012, especially Footnote 3 therein). Third, the use of initiation times renders the current results more comparable to other findings in the literature that utilized the same apparatus (Janczyk et al., 2014; Kunde, Müsseler, & Heuer, 2007; Kunde et al., 2012). Regarding the second task, it would also have been possible to measure RT as the total response time, i.e., the time from stimulus onset through response initiation by leaving the home key until pressing either the left or the right key. To remain consistent across both tasks, however, we chose to register RTs with response initiation also for this latter task.

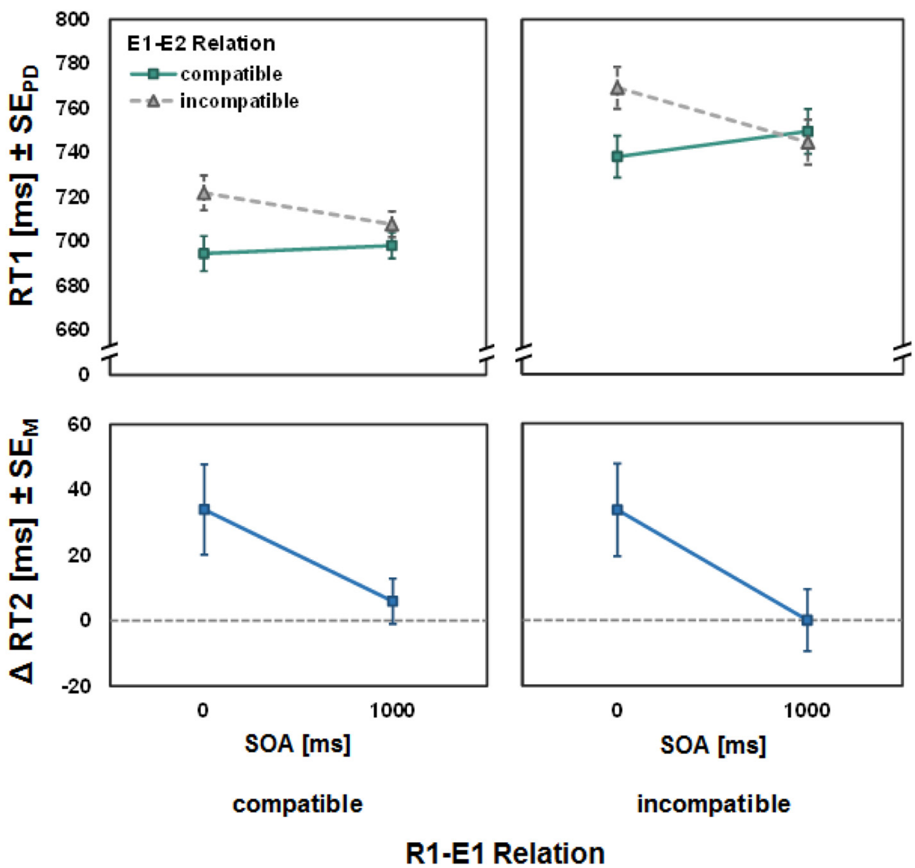

Fig. 2. Reaction times for Task 1 (RT1) and Task 2 (RT2). The upper panels show RT1 for compatible (left panel) and incompatible (right panel) R1-E1 relations. There was clear backward crosstalk for short SOAs, but not for long SOAs, and backward crosstalk was independent of the R1-E1 relation. That is, participants were faster in Task 1 when the movement of the lever on the screen (effected by the first task response) was compatible with the left hand movement (second task) than when both movements were incompatible. There was also a strong effect of R1-E1 relation, with participants showing faster responses when the movement of the lever on the screen and of the controller operated by the right hand (Task 1) were compatible. Error bars depict standard errors of the paired differences (SE_{PD}; Pfister & Janczyk, 2013), computed separately for each combination of SOA and R1-E1 Relation. The lower panels show the difference in RTs between the compatible and incompatible condition in Task 2 [$RT_{incompatible} - RT_{compatible}$], separately for the compatible and the incompatible R1-E1 relation. The difference is shown because a pronounced effect of SOA would have rendered the graphs unreadable otherwise (raw data are reported in Table 1). There was strong evidence for forward crosstalk, especially for short SOAs, i.e., participants responded faster in Task 2 when the E1-E2 relation was compatible than when it was incompatible. This effect was again independent from the R1-E1 relation. Error bars depict standard errors of the mean (SE_M).

3. Results

3.1. Task 1 (Lever Task)

Mean RTs for Task 1 are shown in Fig. 2 and Table 1. Our data indicate clear backward crosstalk, i.e., RTs in the first task were significantly faster when the lever movement on the screen (effected by the first task response) and the left hand movement (second task) were compatible rather than incompatible, $\Delta RT = 16$ ms, $F(1, 36) = 13.17$, $p = .001$, $\eta_p^2 = 0.27$. This result was mostly driven by pronounced backward crosstalk when Task 1 and Task 2 were presented at the same time (SOA = 0 ms), whereas no significant backward crosstalk effect emerged when the second task was presented after the first task (SOA = 1000 ms); interaction E1-E2 Relation × SOA: $F(1, 36) = 7.29$, $p = .010$, $\eta_p^2 = 0.17$, simple effects analysis: $\Delta RT_{0ms} = 29$ ms, $t(36) = 4.06$, $p < .001$, $d = 0.67$; $\Delta RT_{1000ms} = 2$ ms, $t(36) = 0.40$, $p = .694$, $d = 0.07$. RTs in the first task further depended on the relation of controller movement of the right hand and lever movement on the screen (i.e., action and action effect of Task 1): participants responded faster if both movements were compatible than when both movements were incompatible, $\Delta RT = 45$ ms, $F(1, 36) = 8.64$, $p = .006$, $\eta_p^2 = 0.19$. Interestingly, this effect did not interact with backward crosstalk, i.e., the R1-E1 relation did not modulate the effects of the E1-E2 relation, $F(1, 36) = 0.57$, $p = .455$, $\eta_p^2 = 0.02$. None of the remaining effects were significant, $ps > .262$.

To further corroborate the finding of an absent interaction between R1-E1 relation and E1-E2 relation (i.e., independent effects of backward crosstalk and R-E compatibility), we re-analyzed the data of the 0 ms SOA, because, if present, an interaction would be expected to show up especially in this setting. The results fully replicated the previous ANOVA with significant main effects for E1-E2 relation, $F(1, 36) = 16.47$, $p < .001$, $\eta_p^2 = 0.31$, and R1-E1 relation, $F(1, 36) = 9.96$, $p = .003$, $\eta_p^2 = 0.22$, but no interaction, $F(1, 36) = 0.15$, $p = .702$, $\eta_p^2 = 0.00$. To assess the evidence for an absence of interaction effects more directly as via omnibus ANOVAs, we further computed the 95% confidence interval for the interaction effect, followed up by an assessment via Bayes Factor analysis.

We determined the interaction effect for each participant by means

Table 1
Mean reaction times (RTs) for Task 1 and Task 2. SOA = Stimulus Onset Asynchrony [ms]; SE_{PD} = standard error of paired differences.

Measure	SOA	R1-E1 relation					
		Compatible			Incompatible		
		E1-E2 relation			E1-E2 relation		
		Compatible	Incompatible	SE_{PD}	Compatible	Incompatible	SE_{PD}
RT1	0	694	721	8	738	769	9
	1000	698	708	6	749	745	10
RT2	0	1167	1201	14	1216	1249	14
	1000	481	487	7	493	493	9

of the following formula (c and i representing compatible and incompatible conditions of E1-E2 relation and R1-E1 relation, respectively):

$$\Delta_{\text{Interaction}} = (RT_{ci} - RT_{cc}) + (RT_{ic} - RT_{ii})$$

The corresponding 95% confidence interval around the mean interaction effect was [−24 ms, 16 ms]. The Bayes Factor for the interaction effect amounted to 5.27 (computed based on the corresponding *t* statistics by using the "BayesFactor" package version 0.9.12-2, running in R3.3.0 and using a scale parameter on the effect size of $\sqrt{2}/2$). Because Bayes Factors > 3 are typically taken to indicate evidence in favor of the null hypothesis this result provides *evidence for the absence* of such an interaction effect rather than *absence of evidence*. Despite the suggestive results of the Bayes Factor analysis, the data could still also be compatible with the assumption of a very small interaction effect rather than a true null effect. To determine a range of plausible effect sizes, we transformed the *F*-statistic into Cohen's d_Z by using the formula:

$$d_Z = \frac{t}{\sqrt{n}} = \frac{\sqrt{F}}{\sqrt{n}} = \frac{\sqrt{0.15}}{\sqrt{37}} = 0.06$$

We then used the "ci.sm" function of the "MBESS" package version 4.3.0 in R to determine a 95% confidence interval round this effect size. This interval was [−0.26, 0.39], thus spanning values of d_Z that are usually assumed to fall below the threshold of small effects ($d_z = 0.30$), though being also compatible with an effect that just exceeds this threshold. When considered in conjunction with the results of the Bayes Factor analysis, we therefore conclude that the interaction effect does not amount to a relevant size and should best be viewed as absent until qualified by further work.

An analysis of PEs (see Table 2) also revealed backward crosstalk: participants made fewer errors in Task 1 when the hand movement of Task 2 was compatible with the lever movement on the screen, $\Delta PE = 1.7\%$, $F(1, 36) = 30.63$, $p < .001$, $\eta_p^2 = 0.46$. Again, this was mainly driven by the difference of errors in the compatible and incompatible E1-E2 relation conditions when Task 1 and Task 2 were presented at the same time, whereas no such effect appeared for long SOAs, interaction E1-E2 Relation × SOA: $F(1, 36) = 16.20$, $p < .001$, $\eta_p^2 = 0.31$, simple effects analysis: $\Delta PE_{0ms} = 3.1\%$, $t(36) = 5.56$, $p < .001$, $d = 0.91$; $\Delta PE_{1000ms} = 0.4\%$, $t(36) = 1.08$, $p = .286$, $d = 0.18$. The data also indicate a main effect of SOA: participants made fewer errors in the first task when the second task was presented 1 s after the first task than when both tasks were presented simultaneously, $\Delta PE = 1.2\%$, $F(1, 36) = 15.6$, $p < .001$, $\eta_p^2 = 0.30$. None of the remaining effects were significant, $ps > .388$.

The ANOVA on the data for an SOA of 0 ms yielded a significant main effect of E1-E2 relation, $F(1, 36) = 30.95$, $p < .001$, $\eta_p^2 = 0.46$, but no effect of R1-E2 relation, $F(1, 36) = 0.06$, $p = .814$, $\eta_p^2 = 0.00$, and, crucially, no interaction, $F(1, 36) = 0.56$, $p = .458$, $\eta_p^2 = 0.02$. When computing the interaction effect as for the RT data, the 95% confidence interval around the interaction effect was [−1.4%, 0.6%] with a Bayes Factor of 4.35. As for the RT data, these results suggest that the absent interaction of E1-E2 relation and R1-E1 relation is indicative of either a very small effect or a true null effect.

3.2. Task 2 (Keypress task)

Mean RTs for Task 2 are shown in Fig. 2 and Table 1. RTs in the second task were significantly faster when the left hand movement (second task) and the lever movement on the screen (effected by the first task response) were compatible. This represents pronounced forward crosstalk, $\Delta RT = 18$ ms, $F(1, 36) = 10.66$, $p = .002$, $\eta_p^2 = 0.23$. As in the first task, this result was mostly due to forward crosstalk when Task 1 and Task 2 were presented at the same time (SOA = 0 ms), whereas no forward crosstalk was found when the second task was presented 1 s after the first task (SOA = 1000 ms), interaction E1-E2 Relation × SOA: $F(1, 36) = 7.34$, $p = .010$, $\eta_p^2 = 0.17$, simple effects analysis: $\Delta RT_{0ms} = 34$ ms, $t(36) = 3.39$, $p = .002$, $d = 0.58$; $\Delta RT_{1000ms} = 3$ ms, $t(36) = 0.56$, $p = .582$, $d = 0.09$. However, in contrast to Task 1, the data did not indicate a general propagation of the R1-E1 relation effect, i.e., the RTs of Task 2 did not depend on the compatibility of lever and controller movement in Task 1 despite a clear descriptive difference between the conditions, $\Delta RT = 28$ ms, $F(1, 36) = 1.28$, $p = .265$, $\eta_p^2 = 0.03$. A significant interaction of SOA and R1-E1 relation revealed that indeed for the long SOA (1000 ms), the R1-E1 relation of the first task did not affect the second task at all. A different picture emerges when Task 1 and Task 2 were presented simultaneously: here, there is a trend towards effect propagation from Task 1 to Task 2, leading to slightly faster RTs in the second task when lever and controller movement in the first task were compatible, interaction R1-E1 Relation × SOA: $F(1, 36) = 7.63$, $p = .009$, $\eta_p^2 = 0.18$, simple effects analysis: $\Delta RT_{0ms} = 48$ ms, $t(36) = 1.76$, $p = .088$, $d = 0.29$; $\Delta RT_{1000ms} = 8$ ms, $t(36) = 0.33$, $p = .741$, $d = 0.05$. As in Task 1, the R1-E1 relation interestingly did not modulate the effects of the E1-E2 relation, i.e., the R1-E1 relation did not interact with forward crosstalk, interaction R1-E1 Relation × E1-E2 Relation, $F(1, 36) = 0.06$, $p = .811$, $\eta_p^2 = 0.02$. Moreover, and not surprisingly, there was a strong effect of the SOA; participants responded much faster in the second task when there was a delay between the two tasks relative to when both tasks were presented simultaneously, $\Delta RT = 720$ ms, $F(1, 36) = 1043.03$, $p < .001$, $\eta_p^2 = 0.97$. The three-way interaction (E1-E2 Relation × R1-E1 Relation × SOA) did not approach significance, $F(1, 36) = 0.08$, $p = .784$, $\eta_p^2 < 0.01$.

The forward crosstalk found for the RTs in Task 2 was also mirrored in the PE data (see Table 2): participants made fewer errors in Task 2 when the hand movement of Task 2 was compatible with the lever movements on the screen than when both were incompatible, $\Delta PE = 2.0\%$, $F(1, 36) = 26.48$, $p < .001$, $\eta_p^2 = 0.42$. As in Task 1, this effect was mostly due to forward crosstalk when Task 1 and Task 2 were presented simultaneously, although simple effects analysis also showed attenuated forward crosstalk for the long SOA, interaction E1-E2 Relation × SOA: $F(1, 36) = 11.63$, $p = .002$, $\eta_p^2 = 0.24$, simple effects analysis: $\Delta PE_{0ms} = 2.9\%$, $t(36) = 6.12$, $p < .001$, $d = 1.00$; $\Delta PE_{1000ms} = 1.0\%$, $t(36) = 2.17$, $p = .037$, $d = 0.36$. Moreover, our

Table 2
Mean error percentages (PE) for Task 1 and Task 2. SOA = Stimulus Onset Asynchrony [ms]; SE_{PD} = standard error of paired differences.

Measure	SOA	R1-E1 relation					
		Compatible			Incompatible		
		E1-E2 relation			E1-E2 relation		
		Compatible	Incompatible	SE_{PD}	Compatible	Incompatible	SE_{PD}
PE1	0	1.8	5.3	0.9	2.0	4.8	0.5
	1000	2.3	2.4	0.5	1.9	2.6	0.5
PE2	0	3.1	5.5	0.6	3.1	6.6	0.7
	1000	3.2	4.2	0.5	3.5	4.5	0.6

data indicate a general trend that participants made fewer errors in the second task when Task 1 and Task 2 were presented with a delay relative to when both tasks were presented at the same time, ΔPE = 0.8%, $F(1, 36) = 2.87$, $p = .099$, $\eta_p^2 = 0.07$. None of the remaining effects were significant, $ps > .246$.

4. Discussion

Effect-based action control in general, and crosstalk during multitasking in particular, rely on the activation of action effect representations (e.g., Eder et al., 2017; Janczyk et al., 2014; Kunde, 2001; Pfister, Janczyk, Wirth, Dignath, & Kunde, 2014). However, theory and previous evidence suggest that both effects occur in different stages during information processing: whereas crosstalk needs to occur in stages allowing for parallel processing of multiple tasks, R-E compatibility is thought to be located during "response selection", the central bottleneck of information processing that is restricted to only one task at a time (Kunde et al., 2012; Wirth et al., 2015). If this holds true, crosstalk and R-E compatibility should occur independently from each other, despite their conceptual similarity.

We tested this prediction in a PRP set-up with the first task involving an R-E compatibility component and the second task allowing for the exploration of crosstalk effects via compatible or incompatible action effects in relation to the first task. The second task was presented either simultaneously with the first task or with a delay of 1000 ms; crosstalk effects were only expected with simultaneous (or close-to-simultaneous) processing of both tasks. A significant interaction of R-E compatibility and crosstalk would indicate that R-E compatibility affects crosstalk (at least to a certain extent), whereas no interaction would indicate independent processes, as theory suggests.[6]

Indeed, our results support the assumption that R-E compatibility and crosstalk occur independently from one another. The participants' performance was facilitated when action effects in Task 1 and Task 2 were spatially compatible and performance was impaired when the action effects were incompatible. Furthermore, performance in Task 1 depended on its R-E relation: if movement of the controller and the subsequent lever movement on the screen were spatially compatible, participants responded faster than when they were spatially incompatible.[7] However, as proposed by theory, these two effects did not interact, resulting in no significant interaction effect in either task. In addition to the virtually absent effect in terms of the observed effect size, follow-up tests suggested that the range of effect sizes that might be compatible with the current data is rather small, and Bayes Factor analysis supported this assessment by indicating evidence for the absence of an interaction effect. That is, effect-based crosstalk is currently best described as occurring independently from effect-based response selection as measured via response-effect compatibility effects.

This observation is interesting for two reasons. First, it suggests that the backward crosstalk between the response in Task 2 (or respectively its body-related re-afferences) occurred relative to the instructed and thus task-relevant movement of the lever tool in Task 1 alone. For example, a required movement to the right in Task 2 facilitated lever movements to the right in Task 1, irrespective of whether this lever movement was brought about by a leftward or rightward movement of the hand. So with respect to backward crosstalk, only the instructed and thus likely intended effects of the two actions counted. Apparently, these effect codes become activated by corresponding stimuli in two tasks concurrently. With respect to the forward compatibility effect, the present data are not very informative, as either the anticipation or observation of the Task 1 response effects (i.e. tool movement) might have biased the response in Task 2. Second, codes of the required hand movements (or its body-related re-afferences) in Task 1 did apparently not become activated in a parallel manner. Otherwise we should have observed an interaction between backward crosstalk and response-effect compatibility, such that backward crosstalk was larger with a compatible R-E relation. This would follow because a certain movement in Task 2, e.g., a "right" movement, would prime both, a "right" movement of the lever and a "right" movement of the hand with a compatible hand-lever assignment, but only the "right" lever movement with incompatible hand-lever assignment. Note that the codes of the hand movements in Task 1 obviously did impact performance (as evident in the strong impact of R-E compatibility) but apparently they did so in a later stage, not shared by two tasks, typically denoted as response selection (cf. Fig. 3).

The model proposed in Fig. 3 is fully compatible with previous accounts that propose a coactivation of responses in an automated fashion (Miller, 1982; Pashler, 1993), especially Hommel's (1998) model of parallel response activation stage prior to response selection proper, which operates in a strictly serial fashion.[8] However, it specifies the process of response activation as a gradual build-up of effect codes. This view is backed up by single-task studies on ideomotor effect anticipations that have proposed response selection and initiation to revolve around a gradually increasing activation strength of relevant effect codes (Kunde, Koch, & Hoffmann, 2004; Shin & Proctor, 2012; Wirth et al., 2016). According to these accounts, responses are initiated when the hypothesized activation strength exceed a certain threshold. This conceptualization begs the question of why effect activation in the slack time of the second task does not affect response selection of this second task more strongly than observed in the present data as well as in previous studies (Janczyk et al., 2014). One possible reason for this pattern of results is suggested by Schubert et al. (2008). These authors distinguished a "bypass model" and an "indirect influence model" to explain backward crosstalk effects. According to the bypass model, pre-bottleneck response activation directly affects response selection (thus bypassing the response selection bottleneck). The indirect influence model, by contrast, assumes that even though responses become activated before the bottleneck stage, current activation is reset when response selection of the second task commences without bypassing the response selection bottleneck. Their data favored the indirect influence model by showing no direct response priming effects for the second task in situations without crosstalk. Assuming that response activation comes down to activating the corresponding effect codes as suggested by ideomotor accounts of human action control would hold that the resetting mechanism of Schubert et al. entails the resetting of currently activated effect codes.[9]

This study therefore supports the idea that simple action effect activation (during the early phase of response production) and the contribution of effect codes for actual response selection and initiation (a process that is thought to underlie R-E compatibility effects) are indeed two distinct processes. The interesting question is whether and how action effect codes contribute to this later, and apparently serially operating, stage of response production. We see two not mutually exclusive possibilities here. First, it might be that the effect codes which make up a response have to be bound together, and that such binding

[6] Additive factors logic holds that an interaction of two experimentally manipulated factors indicates that these manipulations at least partly pertain to a common processing stage (Sternberg, 1969). This may also hold true for only parts of the employed manipulations.

[7] We also observed a trend towards an impact of R1-E1 relation on the RTs of the second task, even though the relevant experimental manipulation pertained exclusively to the first task. This trend likely reflects propagation of the effects in Task 1 to Task 2: As the longer processing for incompatible rather than compatible R-E relations supposedly occupies the bottleneck stage of information processing, the additional processing time directly prolongs RTs of the second task (Pashler, 1994). Indeed, effect propagation of R-E compatibility effects has been observed repeatedly in previous work (e.g., Kunde et al., 2012; Wirth et al., 2015).

[8] The model also does not contradict additional parallel activations such as those relating to semantic categorizations (Fischer, Miller, & Schubert, 2007; Logan & Schulkind, 2000; Oriet, Tombu, & Jolicoeur, 2005).

[9] We thank Torsten Schubert for stimulating this discussion.

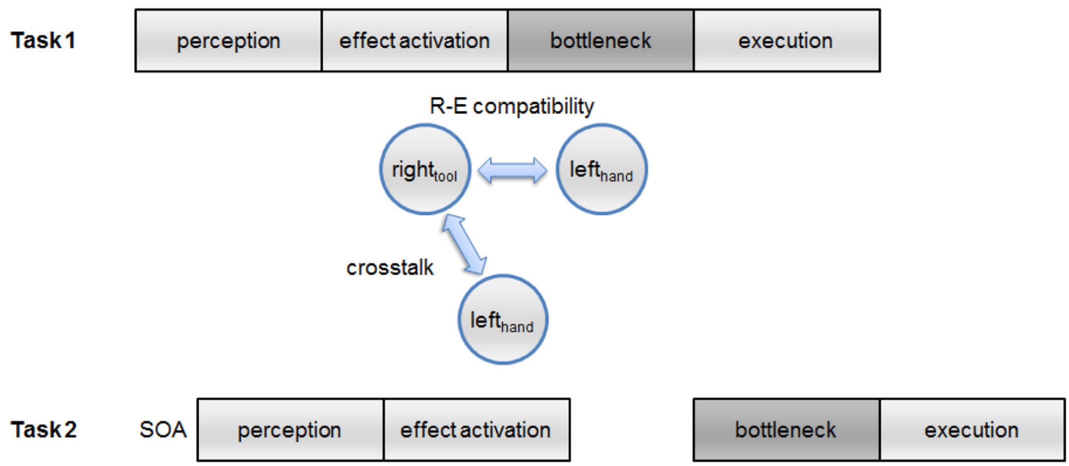

Fig. 3. Information processing stages assumed in dual tasking, and the tentative activation of various effect codes. Applied to the present experimental setup, crosstalk between features of the Task 2 response and the Task 1 tool movement occur in a parallel stage of processing and these stages overlap at least for short stimulus-onset asynchronies (SOAs). Response-effect (R-E) compatibility effects between tool movement and hand movement, by contrast, arise in a later, serial stage.

can occur for only one task at a time (Hommel, 2009). Shortly, the "bottleneck" in dual tasking might reflect binding of features to an event which we call a "response". This explanation would correspond to observations showing that keeping a selected action in mind interferes with the initiation of other actions that would require these bound features as well (Fournier, Gallimore, Feiszli, & Logan, 2014; Stoet & Hommel, 1999; but see Kunde, Hoffmann, & Zellmann, 2002).

However, R-E compatibility effects occur (though to a lesser extent) even when response selection cannot contribute to performance, because responses are fully selected and only remain to be initiated (Kunde et al., 2004; Shin & Proctor, 2012; Wirth et al., 2016). This would suggest that effect codes contribute to action initiation as well, perhaps because even bound effect codes need additional, controlled activation to reach a certain execution threshold (or activation decrement in case they are intentionally withheld). This would also suggest that the initiation of a response might pose a bottleneck to dual tasking (de Jong, 1993). Interestingly, a similar idea was postulated by William James in 1890. He stated that there must be a difference between mere imagery or activation of action effects and the actual response initiation, a "resolve that the act shall ensue" that he termed "fiat" (James, 1890, p. 337). It will be important for future research to reveal how effect codes contribute to action initiation and to which extent this is part of the "bottleneck" that is so consistently observed in dual tasking.

5. Conclusions

Our study supports current theoretical accounts of effect-based response selection in the capacity-limited stage and effect-based crosstalk in the non-limited stages of information processing during multitasking. Although conceptually similar, both processes seem to be different in principle and occur at different stages during task processing.

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