Memory & Cognition
2007, 35 (5), 1175-1186

The costs and benefits of cross-task priming

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Two lines of research on cross-task priming yield opposite results. Research on repetition priming observed positive priming, whereas research on the role of priming in task-switching observed negative effects. We combined the two types of design. In the transfer phase of our paradigm, subjects performed task B either as a pure block (BBB) or as a switch block (ABAB). We presented items which were either unprimed or primed by prior presentation during a preceding priming phase performed on task A. Amongst others, the priming effect is determined by two factors: First, the more operation time the system needs during the probe event, the higher the likelihood to obtain priming. Protracting operation time by reducing stimulus quality favors positive priming, whereas providing more operation time by making subjects switch between tasks favors negative priming. Second, the strength of the memory trace of the prime event determines whether that trace can possibly yield negative priming, in that only strong traces can be retrieved together with the associated task/response.

Priming refers to a change in the speed or accuracy of processing of a probe event, as a result of prior experience with the same or a related prime event. Priming can refer to stimuli, responses, or entire stimulus–response (S–R) episodes and it can facilitate or hamper processing (positive priming and negative priming, respectively). The effect of a priming event may dissipate after a few seconds or it may survive minutes or even days. For a review, see Richardson-Klavehn and Bjork (1988) and Henson (2003).

Up to now the conditions for, and the relationships between different forms of priming are rather unclear. Among other things, it remains an open issue how positive priming relates to negative priming, and whether short-term and long-term priming reflect the same mechanisms. The present article aims at understanding how the task context in which a prime event occurs affects priming. To anticipate, we will show that, across a switch of task, the same priming events may speed up or impede subsequent processing of a recurring stimulus, depending on factors related to the prime event (e.g., number of accumulated processing episodes) as well as factors related to the probe event (e.g., the probe trials' sensitivity to priming). That is, repetition-prime events can have utterly different effects, depending on specific aspects of the experimental set-up—an important insight on the way toward an integrative theory of priming.

Our experiments were motivated by an apparent empirical inconsistency. On the one hand, a number of studies have found *positive* priming from one task context to another, that is, a prime-induced facilitation of probe processing even when prime and probe appeared in different tasks. For example, words presented in a word-pronunciation task facilitate responses to the same words appearing in a lexical-decision (word/nonword) task (Monsell, 1985; Scarborough, Gerard, & Cortese, 1979), and vice versa (Monsell, 1985; Logan, 1990). Similarly, encountering a picture in a task requiring facial-expression judgments (smiling/not smiling?) or gender classification (male/female?) facilitates familiarity judgments on this picture (Ellis, Young, & Flude, 1990).

On the other hand, *negative* cross-task priming has consistently been observed in experiments on the influence of S–R priming in task-switching (Waszak, Hommel, & Allport, 2003, 2004, 2005; see also Koch & Allport, 2006; Koch, Prinz, & Allport, 2005; Wylie & Allport, 2000, but see also Yeung & Monsell, 2003). In the experiments of Waszak and colleagues, participants orally named either the word- or the picture-constituent of incongruent (Stroop-like) picture–word conjunctions (e.g., the picture of a LION with the word apple superimposed on it), switching task every third trial. Within the word-reading task, participants could encounter picture–word stimuli that had never been presented in the context of picture-naming (unprimed stimuli, i.e., items with no cross-task priming) as well as picture–word stimuli that they had picture-named previously (primed items). Word-reading reaction times (RTs) in response to primed items were much slower than to unprimed items. This effect occurred even when more than 200 trials intervened between the prime

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event and the probe. In view of these results, Waszak et al. (2003) suggested that, when people carry out a particular action in response to a particular stimulus, they encode the underlying stimulus- and response-related codes into an integrated S–R episode (cf. Allport, 1987; Hommel, 1998; Hommel, Pösse, & Waszak, 2000; Logan, 1988, Neill, 1997). If the stimulus of the encoded S–R episode is then encountered again, the whole S–R episode is automatically retrieved, making switching between arbitrary tasks using the same stimuli more difficult. In fact, Waszak and colleagues (2003) claimed that associations are formed between *all* the encoded constituents of the action-event, not only between the immediate stimulus and its response, but also with the distal goal of the action, the task, and task-specific processing operations. For brevity, we shall refer to these postulated stimulus–task-action links as S–R episodes. We will come back to this issue at the end of the experimental section, just before the general discussion.

The present study addressed the question of why repetition priming produces benefits under some conditions but costs under other, seemingly similar conditions. As considered by Waszak and colleagues (2005), the answer to this question may be related to the main difference between their and the other studies: While Waszak et al. used a typical task switching procedure, all the other studies used a design in which the tasks were administered in a blocked fashion. Indeed, Waszak et al. (2003) observed negative priming on task-switch trials only—a condition that does not occur in a block design.[1] In a typical task switching experiment, subjects are required to switch frequently among a small set of simple tasks (e.g., Allport, Styles, & Hsieh, 1994; Koch, 2003; Logan & Bundesen, 2003; Mayr & Keele, 2000; Meiran, 1996; Rogers & Monsell, 1995). Usually, subjects' responses are considerably slower after a task switch than if they repeat the task they performed in the preceding trial. This RT cost is called task-switch cost (for a review see Monsell, 2003). The task-switch cost is usually reduced, if the subject has advance knowledge of the upcoming task and enough time to prepare for it (e.g., Rogers & Monsell, 1995). However, task preparation generally does not eliminate the switch cost completely. Rather, the reduction in switch cost usually reaches a substantial asymptote, the 'residual cost.' Moreover, task performance on repetition trials within a task switching context is slower than if just one task is performed throughout the block (mixing costs).

Task switch costs are, thus, a heterogeneous phenomenon and most authors acknowledge that task-shift costs are due to a plurality of causes. Amongst others, it probably reflects a kind of time-consuming, endogenous, task-set-reconfiguration process that prepares the cognitive system for the upcoming task (e.g., Rogers & Monsell, 1995; Rubinstein, Meyer & Evans, 2001). However, more important in the present context, switching to a new task may also make the system more vulnerable to conflict induced by bottom-up processes: In terms of the "task-set inertia" (TSI) model (Allport et al., 1994), switching from, say, picture-naming to, say, word-reading, faces the problem that the picture-naming task-set is still somewhat activated and, thus, competes with the word reading task-set. Not so on repeat trials (and especially in pure blocks), where TSI from the preceding trial serves only to strengthen the relevant task-set, so that word-reading is not interfered with by the competing stimulus–response associations.

Before we address the question of why switching tasks gives rise to negative cross-task priming in more detail in Experiment 4, we will for the sake of simplicity assume that switching a task is just one way of providing more operation time for stimulus-induced retrieval processes: As retrieving a whole processing episode (including response and task context) takes some time, it seems obvious that the retrieved memory trace affects current processing more likely the later in time the targeted processes occur (see Logan, 1988). Operation time may thus be one factor that determines whether negative cross-task priming is observed: The more time spent on processing the probe the stronger the impact of old episodes. It is less clear which factors are relevant for positive cross-task priming. One possibility is that these effects are due to a different process, a process that relates more to the activation of stimulus codes than to the retrieval of S–R codes. That is, positive priming may make use of left-over activation of (perceptual and/or semantic) stimulus codes from prime processing. If so, processing the probe should be facilitated independently of the current task and, more importantly, independent of the difficulty of this task. Accordingly, both fast and slow responses to the probe should be facilitated, whereas only slow responses will be affected by the retrieval-based interference from previously acquired processing episodes. As a consequence, facilitation will dominate under easy conditions (such as pure task blocks and repetition trials) and interference under difficult conditions (such as switch trials), thus producing the observed cost-benefit pattern. Another possibility is that operation time is important for both positive and negative priming to unfold, and other factors determine the sign of the priming effect. If so, it may be possible to find negative priming in pure tasks and positive priming in mixed tasks.

To investigate the impact of blocking versus mixing tasks empirically, we employed a paradigm that is typically used in studies on long-term cross-task priming effects (e.g., Logan, 1990). That is, participants were presented with two blocks of trials. First, a priming phase, in which participants performed one task on a particular set of items. In this phase, so the reasoning goes, obligatory encoding (Logan, 1988, 1990; see also Hommel, 1998; Hommel, et al., 2000) should cause a representation of the item and its context (task, response) to be stored in memory. Second, there was a transfer phase, in which participants performed a task different from the one in the priming phase. In this second phase, participants are presented with primed items (i.e., items which already appeared during the priming phase) as well as unprimed items (i.e., items that did not appear in the priming phase). Any RT difference between primed and unprimed items, so the reasoning continues, must be due to the retrieval of information encoded during the priming phase. The novel feature of our paradigm is that the transfer phase differed in a central aspect from typical cross-task priming paradigms: We did not only test participants performance in pure blocks, i.e., in runs of the same task, but also in mixed blocks, in which participants had to alternate between the prime task, used in the priming phase, and the probe task introduced in the transfer phase. This enabled us to directly compare priming when tested in pure task performance, as it is usually assessed in long-term cross-task priming studies, with priming tested in alternating task performance, as in the studies from Waszak et al. (2003, 2004, 2005). In compliance with the hypothesis outlined above, we expected that the same priming events would yield different effects in pure and mixed blocks, presumably positive priming in the former and negative priming in the latter.

Moreover, presenting mixed and pure blocks in an order that was balanced across subjects enabled us to investigate the effect of the lag between priming and transfer phase (simply by investigating the effect of whether participants performed the pure block or the mixed block first). The question of the lag between priming and transfer phase is important because priming effects reported in the literature show a considerable variability in temporal stability. Some effects last up to minutes or even hours (e.g., DeSchepper & Treisman, 1996; Lowe, 1998; Waszak et al., 2003), while others seem to dissipate after some seconds (Hommel, 1998). Some effects survive intervening events, some do not (see e.g., Tipper, Weaver, Cameron, Brehaut, & Bastedo, 1991). To know about the influence of time lag and intervening events on probe trial performance is, thus, an important element for the quest of an integrative theory of priming. To anticipate, we will show that the order in which mixed and pure blocks are administered has a dramatic effect on performance.

EXPERIMENT 1

The first experiment was designed to assess priming from an "animate/inanimate" semantic categorization (AI) task to a "large/small" semantic categorization (LS) task under both pure and alternating task conditions in the transfer phase. (For the LS task, a cabinet in the laboratory served as the reference object.) In the priming phase, participants made animate/inanimate judgments on target pictures (line drawings of familiar animals or objects). In Experiment 1, each picture (of the primed item set, see below) appeared five times in the priming phase, presented as a pure block (AAA . . .). In the transfer phase, each participant worked through two different types of block. In both types participants were transferred to the small/large task. In the pure blocks of the transfer phase, participants continuously made the small/large judgment without any intervening trials of the animate/inanimate task (BBB . . .). By contrast, in the mixed blocks of the transfer phase, participants had to switch between the animate/inanimate task and the small/large task (ABABA . . .). Block order (pure block first vs. mixed block first) was counterbalanced across subjects. An additional control group of subjects was introduced to separate the effects of the time lag between the first and the second block from the proactive interference that the first block could possibly have on the second block (for details see below). In both pure and mixed blocks, RTs were measured in response to primed items (i.e., items which already appeared during the priming phase, in the different task context) as well as unprimed items (i.e., items that did not appear in the priming phase). In the mixed blocks of the transfer phase, the prime task was performed on an additional set of items different from the primed and unprimed item sets and, as for the pure blocks, priming was tested for the small/large task only.

Method

Participants

Twenty participants, 6 male and 14 female with a mean age of 22 years, took part in the main experiment. Twenty more participants, 9 male and 11 female with a mean age of 23 years, took part in the control experiment (see below). All participants received a remuneration of about €7.5. Both main and control experiment lasted about 40 minutes. All participants were native German speakers and none reported having participated in a similar experiment.

Apparatus and Stimuli

The experimental material consisted of 72 line drawings, which were presented on a 17-in. Phillips T17 monitor. They appeared in black on a white background at the center of the screen. The mean extension of the line drawings was approximately $1.9^{\circ} \times 1.9^{\circ}$. Line drawings and normative data were obtained from the Snodgrass-Vanderwart Set of Standardized Pictures (Snodgrass & Vanderwart, 1980). The picture names were all either of one or two syllables and the pictures were conceptually and linguistically as unambiguous and familiar as possible. The 72 pictures were assigned to three item-subsets (24 pictures each): set P (primed items), set U (unprimed items) and set F ("filler" items). The subsets were matched as strictly as possible for syllable-length, name agreement, image agreement, familiarity and complexity. Sets P and U were divided randomly for each participant into subsets P-pure, P-mixed, U-pure, and U-mixed, respectively (12 pictures each).

Design

The experiment began with the priming phase. Participants performed a pure AI task. This phase included five complete randomized iterations of all stimulus-items of item-set P, amounting to 120 AI trials. In the following transfer phase, all participants performed a pure block and a mixed block.

In the mixed block, participants alternated between the AI task and the LS task (AI LS AI LS and so on). In both tasks participants responded with a left or a right keypress on the response pad. The LS task was performed on the items of the sets P-mixed and U-mixed. Since the AI task was merely meant to induce task competition in the mixed blocks, it was performed on the items of set F ("filler" items). Accordingly, there was no item-specific cross-task priming within the mixed blocks of the transfer phase.

In the pure block, participants were presented with the items from the P-pure and U-pure sets. As in the mixed block, U-pure and P-pure items were presented in alternation with F items. However, in the pure block, the task (LS) did not alternate. This was done in order to hold constant the mean lag between the S–R episodes in the priming phase and the S–R episodes in the transfer phase for both types of block. In both kinds of block, set P, set U and set F items were presented three times. Thus, participants performed 144 trials in each of the two blocks. Half of the participants began with the pure block (Pure first); the other half began with the mixed block (Mixed first).

Control group. We ran an additional group of subjects to allow separating the effects of the mere time lag between the first and the second block of the transfer phase on the one hand from the proactive interference that the intervening events of the first block could possibly have on the second block on the other. To do so, we included a group of subjects which—after the priming phase that was identical to the other groups—was presented with a mixed block only. Importantly, in this group, the beginning of the mixed block was delayed for the amount of time subjects would have spent in a pure

Table 1
Experiments 1–4: Reaction Times (RTs, in Milliseconds, With *SE*s) and Errors (ER, %) for the Probe Events, Separated for Pure and Mixed Blocks, Block Order and Number of Prime Events, and Stimulus Set

Block Type	Set	Mixed First RT	Mixed First *SE*	Mixed First ER	Pure First RT	Pure First *SE*	Pure First ER	Mixed Delayed RT	Mixed Delayed *SE*	Mixed Delayed ER	Mixed-High RT	Mixed-High *SE*	Mixed-High ER	Pure-Low RT	Pure-Low *SE*	Pure-Low ER
Experiment 1																
Mixed	P	1,003	79	4.7	1,057	107	6.1	1,042	62	2.9						
	U	945	88	4.7	1,197	165	5.6	1,020	61	2.2						
Pure	P	560	24	7.9	565	26	6.9									
	U	577	32	7.3	568	32	6.0									
Experiment 2																
Mixed	P	1,319	89	5.9	1,180	71	3.7									
	U	1,247	68	4.5	1,232	78	4.8									
Pure	P	639	22	7.7	672	15	6.1									
	U	628	20	6.5	645	16	6.3									
Experiment 3																
Mixed	P	1,059	67	6.8	1,102	79	4.9									
	U	1,121	68	5.1	1,094	86	5.9									
Pure	P	589	17	8.9	633	30	5.7									
	U	593	16	9.1	624	26	4.0									
Experiment 4																
	P										1,088	60	6.5	1,058	55	16.4
	U										1,063	56	6.0	1,093	61	17.3

block (8 min). In the mean time, subjects listened to Ravel's Bolero. (We did not include a corresponding pure block control group, because, as you will see below, we did not observe any priming in the pure blocks.) The performance of this control group, so the reasoning goes, should reflect the effect of the mere time lag between priming and transfer phase. By contrast, the performance of the Pure first group which, with reference to the priming phase, performed the mixed block at the same point in time as the control group, should reflect both time-based decay and proactive interference from the intervening events of the pure block to the mixed block.

Procedure

The 120 AI priming trials were presented in a single block. The participant's keypress started the block. The stimuli were presented in a black square frame that remained on the screen throughout the whole block. On each trial, the screen remained blank (except for the frame) for a 500 msec interval. Then the task cue, the letters "B U" (the initial letters of the German words for "animate inanimate" ("belebt unbelebt")) which extended 0.5º vertically and 0.7º horizontally, appeared to the left and to the right of the square frame (in a distance of about 2.5º from the center). Simultaneously with the task cue, the target picture appeared. Cue and stimulus remained on the screen until the participant's response. After the participant responded to the stimulus the procedure repeated.

The 144 trials of each of the two blocks of the transfer phase (pure, mixed) were also presented in a single block each. The procedure was the same as in the priming phase, except for the cues. In the LS trials, i.e., on each trial of the pure block, and on each second trial of the mixed block, the cue consisted of the letters "G K" (the initial letters of the German words for "large small" ("gross klein")) which appeared above and below the square frame. For the AI trials of the mixed block, the cue was the same as in the priming phase.

Results

Main and Control Experiment

Group means of median RTs and error rates are shown in Table 1. Accuracy was high (main experiment: $M = 93.8\%$, $SD = 3.1\%$; control: $M = 97.7\%$, $SD = 2.1\%$) and none of the differences between primed and unprimed items reached significance. Thus, a speed–accuracy tradeoff cannot account for the results. RTs resulting from erroneous trials were excluded from the analysis. The results of the transfer phase are illustrated in Figure 1, which shows the priming effect (RT of unprimed items − RT of primed items) separated for pure and mixed blocks, and—as concerns the main experiment—block order (i.e., whether participants performed the pure block or the mixed block first).

Main Experiment

An ANOVA was run on the median RT data including the within-participants factors block type (pure vs. mixed) and stimulus set (P vs. U), and the between-participants factor block order (pure first vs. mixed first). The main effect of block type [$F(1,18) = 53.037$, $p < .001$] was qualified by a significant block type × stimulus set × block order interaction [$F(1,18) = 7.006$, $p = .02$]. As indicated by the asterisks in Figure 1, one-tailed t tests confirmed the priming effect to be significant for the two mixed blocks ($p < .05$ in both cases). The same ANOVA run on the error data did not yield any significant effect.

Control Experiment

An ANOVA was run on the RT data of the mixed block of the control group (mixed delayed) and the mixed block of the pure first group. The ANOVA included the within-participants factor stimulus set (P vs. U) and the between-participants factor block type (mixed delayed vs. mixed block of the pure first group). The main effect of stimulus set [$F(1,28) = 4.715$, $p < .05$] was qualified by a significant interaction of block type × stimulus set [$F(1,28) = 9.002$, $p < .01$]. As indicated by the asterisks in Figure 1, a one-tailed t test confirmed that the priming effect of the mixed delayed block, too, was statistically significant ($p < .05$). The same ANOVA run on the error data did not yield any significant effect.

Another ANOVA was run on the RT data of the mixed block of the control group (mixed delayed) and, this time, the mixed block of the Mixed first group. The main effect of stimulus set [$F(1,28) = 7.91$, $p < .01$] was the only significant effect. The same ANOVA run on the error data did not yield any significant effect.

Discussion

The pattern of result is clear-cut: There was substantial transfer from the AI priming phase to LS performance in the transfer phase. However, priming was observed in mixed blocks only. What is more, it strongly depended on the context in which the mixed block was performed. Considerable *negative* priming was observed when the mixed block immediately followed the priming phase (mixed block of mixed first group) and also when the mixed block was delayed. By contrast, strong *positive* priming was observed when the mixed block followed the pure block. These results can be accounted for by the following principles.

First, the probability that priming is observed at all depends on the operation time available for episodic retrieval: the more time elapses until response execution, the more likely memory traces come into effect. We will refine this assumption in Experiment 4. Since responses are strongly delayed in mixed blocks, priming effects are much easier to observe in mixed blocks than in pure blocks. Second, the negative cross-task priming is not subject to a strong time-based decay as witnessed by the fact that there was no significant difference between the negative priming in the mixed block of the mixed first group and the priming in the mixed delayed group. Third, the occurrence of intervening trials of the same task as the probe task has a strong influence on priming: for the Pure first group, priming in the mixed block was positive. It seems that performing one and the same task set for a large number of trials sets off prior associations of the same kind of stimuli with another task/response. Similarly, Wickens (1972) showed that successive presentation of different items produces interference on the memory for items from the same conceptual category. However, the proactive interference does not wipe out the whole memory trace. Rather, it obliterates the link between stimulus and response such that the only effect of the prior processing episodes was the RT benefit of repeating the stimulus item.

EXPERIMENT 2

In the introduction we suggested a possible answer to the question of why Waszak and colleagues (2003, 2004, 2005) found an RT cost of item-specific cross-task priming, but not the more common RT benefit (e.g., Logan, 1990). We suggested that the retrieval of a whole processing episode (including task and/or responses) is relatively time-consuming and, accordingly, takes place only if the operation time available for episodic retrieval is rather long (as in mixed blocks). In Experiment 1, we had hoped to replicate both positive and negative priming effects in the same experiment, that is, negative effects in mixed blocks and positive effects in pure blocks. Contrary to these expectations we did not find any priming in the pure blocks.

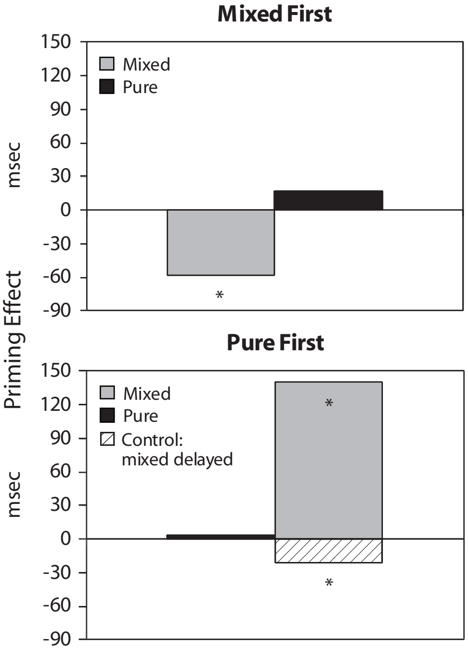

Figure 1. Experiment 1. Priming effect (RT of unprimed items − RT of primed items) separated for 1) pure and mixed blocks, and 2) block order. *$p < .05$, one-tailed *t* test.

One reason for that may be the stimulus material we used, which to our knowledge was not employed by any previous study showing positive cross-task priming. Therefore, we sought to replicate Experiment 1 with stimuli and tasks that have already been shown to produce positive effects in pure blocks. Franks, Bilbrey, Lien, and McNamara (2000) report a series of experiments investigating cross-task priming effects for a variety of task combinations in pure block performance. For all experiments, Franks and colleagues used word stimuli. In accordance with the majority of the literature, they found positive cross-task priming for almost all task combinations. (In none of the 13 experiments they found significant negative priming!) Most relevant for the present study is Franks et al.'s Experiment 7, in which they used the same tasks that we employed in Experiment 1. As for the other task combinations they explored, Franks and colleagues observed significant positive priming from the AI to the LS task (49 msec). With this demonstration in mind, we replicated Experiment 1 (the main experiment only) but used word stimuli instead of line drawings, thus making the pure blocks of Experiment 2 very similar to Experiment 7 of Franks and colleagues.

Method

Twenty-six participants, 9 male and 17 female with a mean age of 23 years, took part for a remuneration of about €7.5. The experiment lasted about 40 min. All participants were native German speakers and none of them had participated in Experiment 1 or a similar experiment. The method was as in Experiment 1, with the

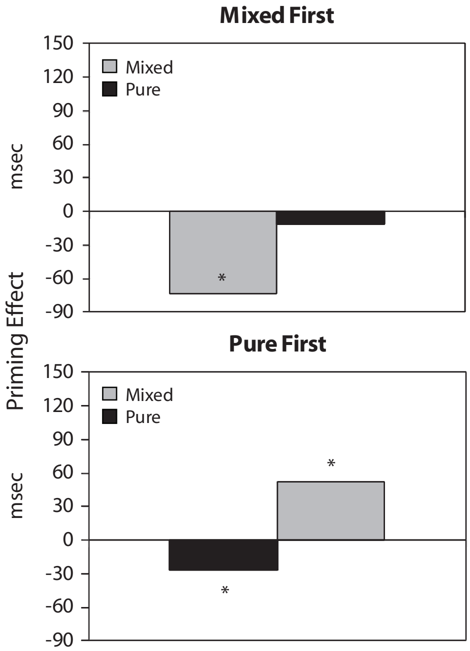

Figure 2. Experiment 2. Priming effect (RT of unprimed items − RT of primed items) separated for 1) pure and mixed blocks, and 2) block order. *$p < .05$, one-tailed *t* test.

following exceptions. The experimental material consisted of 72 words (≈1.2º × 0.7º), presented in black on a white background at the center of the screen. The words were identical with the names of the pictures used in Experiment 1.

Results

Accuracy was again very high (M = 94.3%, SD = 4.4%). RTs resulting from erroneous trials were excluded from the analysis. The results of the transfer phase are illustrated in Figure 2, which shows the priming effect (RT of unprimed items − RT of primed items) separated for pure and mixed blocks, and block order.

An ANOVA was run on the median RTs including the within-participant factors block type (pure vs. mixed) and stimulus set (P vs. U), and the between-participants factor block order (pure first vs. mixed first). The main effect of block type [$F(1,24) = 164.31, p < .001$] was qualified by two significant interactions: stimulus set × block order [$F(1,24) = 5.51, p < .05$] and block type × stimulus set × block order [$F(1,24) = 13.37, p < .01$]. As indicated by the asterisks in Figure 2, one-tailed *t* tests confirmed the priming effect to be significant for the two mixed blocks and for the pure block when performed first ($p < .05$ in all cases). The same ANOVA run on the error data yielded a significant main effect of block type [$F(1,24) = 5.88, p < .05$], with pure blocks yielding slightly more errors than switch blocks. This indicates that there might be some speed–accuracy trade-off between block types. (However, this was the only time we observed this effect.) More importantly, the main effect of stimulus set did not reach significance, nor did stimulus set take part in a significant interaction. The priming effect can, thus, not be attributed to a speed–accuracy trade-off.

Discussion

Figure 2 shows that, with respect to the mixed blocks, the results of Experiment 1 were replicated. Substantial *negative* priming was observed for the "mixed first" group, whereas substantial *positive* priming was observed for the "pure first" group. In contrast to Experiment 1, there was also significant priming in the pure block of the "pure first" group. This transfer effect in the pure block was negative. Most importantly, these observations confirm our conclusions from Experiment 1, but there are two more relevant implications.

First, the findings support our assumption that providing more operation time for retrieval increases the likelihood to obtain cross-task priming effects. Note that the RT level in the pure blocks of Experiment 2, in which we used word stimuli, is much higher than in Experiment 1, in which we used line drawings (568 vs. 647 msec). The mean RT difference between the experiments is probably due to the fact that the tasks we employed engage perceptual-conceptual processes involving the referent of the stimulus presented, in contrast to properties of the stimulus per se. With the word stimuli used in Experiment 2, this was likely to induce the strategy to create an image of the word referent before making the judgment. This made RTs slower than in Experiment 1 and provided more operation time for stimulus-induced retrieval processes—with the consequence that negative priming occurred even in pure blocks.

Second, although we were successful in demonstrating a reliable priming effect in a condition that was similar to those of Franks and colleagues (2000), what we got was negative priming but not the positive priming effect obtained by these authors. Thus, we seem to have identified the factor that is responsible for the presence of priming effects (i.e., design factors affecting operation time) but not yet all the factors that determine the sign of the effect. Experiment 3 sought to fix that.

EXPERIMENT 3

The aim of Experiment 3 was to address the empirical inconsistency between the findings of Franks et al. (2000), who obtained positive priming in pure blocks, and our own observation of negative priming in pure blocks in Experiment 2.

Models of human memory and skill acquisition assume that accumulating more episodic memory traces leads to faster and more efficient retrieval (e.g., Logan, 1988; Logan & Etherton, 1994). Accordingly, one would expect that the associative strength between a stimulus and task-related codes increases as a function of the number of trials a given item is presented under the prime task (the AI task in our case). In Experiments 1 and 2 each item of set P was presented five times. Apparently, this was sufficient to create a link between the item and the task/response as witnessed by the strong negative priming effects found in the transfer phase of both Experiment 1 and Experiment 2. An obvious prediction is that reducing the number of prime trials should weaken the link between stimulus and task, which in turn should decrease the probability that prime activation by the probe spreads to the associated task codes. If so, negative priming should turn into positive priming. This prediction is further corroborated by the fact that, in the study of Franks et al. (2000), each stimulus word was presented only once in the prime task (AI task), that is, five times less than in our Experiment 2. It is, thus, plausible to assume that the difference in sign between the priming effects obtained by Franks et al. on the one hand and in our Experiment 2 on the other is due to the fact that, in the study of Franks and colleagues, a single priming event was not sufficient to create a stable link between stimulus and task. We tested this consideration by replicating Experiment 2 with only single pairings of prime items and the prime task.

Method

Twenty-six participants, 10 male and 16 female with a mean age of 23 years, took part for a remuneration of about €7.5. The experiment lasted about thirty minutes. All participants were native German speakers and none of them had participated in one of the previous experiments or in a similar experiment. The method was as in Experiment 2, except that the priming phase included only one iteration of all stimulus-items of item-set P.

Results

Accuracy was again high (M = 93.6%, SD = 4.9%). RTs resulting from erroneous trials were excluded from the analysis. The results of the transfer phase of Experiment 3 are illustrated in Figure 3.

An ANOVA was run on the median RTs including the within-participant factors block type (pure vs. mixed) and stimulus set (P vs. U), and the between-participants factor block order (pure first vs. mixed first). The main effect of block type [$F(1,24) = 70.54$, $p < .001$] was qualified by three significant or almost significant interactions: stimulus set × block order [$F(1,24) = 6.95$, $p < .05$], stimulus set × block type [$F(1,24) = 3.86$, $p = .06$], and block type × stimulus set × block order [$F(1,24) = 3.70$, $p = .06$]. As indicated by the asterisks in Figure 3, one-tailed t tests confirmed the priming effect to be significant for the mixed block when performed first ($p < .01$). The same ANOVA run on the error data did not yield any significant effect. Thus, there was again no speed–accuracy trade-off.

Discussion

The results of Experiment 3 are clear-cut. Only the mixed block of the "mixed first" group showed a priming effect. Moreover, in strong contrast to Experiment 2, the transfer effect was facilitatory. This pattern of results was to be expected, if one assumes that the more traces accumulate in memory during the priming phase, the stronger the effect of these traces in the transfer phase and the longer the effect of the traces persists (e.g., Logan, 1988, 1990; Logan & Etherton, 1994). In Experiment 2, five repetitions per item created an S–R association strong enough to affect processing in the transfer phase negatively. In Experiment 3, by contrast, a single presentation of each item during the priming phase was not sufficient to establish a stable link between stimulus and task codes. Consequently, the priming effect was facilitatory from the outset.

Note that we do not assume that positive priming is unaffected by the number of stimulus repetitions. It is just that in a *cross-task* priming paradigm, a sufficient number of repetitions in the priming phase might strengthen the S-Task association up to the point where negative transfer rules out positive priming in the transfer phase (given that the R-selection stage is sufficiently slow). Evidently, if prime and probe tasks were identical, we would expect the number of prime trials to influence RTs. This assumption is corroborated by the study from Grant and Logan (1993) who report *repetition* priming effects that increase with increasing number of repetitions during the learning phase.

However, one aspect of the results of Experiment 3 was unexpected. Since Franks et al. (2000) observed strong positive priming in pure block performance, we expected also to find positive priming in both mixed and in pure blocks (at least when performed first). Interestingly, the mean RTs reported by Franks et al. (Experiment 7; primed items: 855 msec, unprimed items: 904 msec) are much larger than the RTs observed in the pure blocks of Experiment 3. In fact, the RTs reported by Franks et al. are almost as large as the mean RTs in the mixed blocks of Experiment 3. We do not know the reason for this tremendous difference in overall RT. However, the pattern of results stresses once more the importance of operation time for the participants' susceptibility to priming.

OVERVIEW: EXPERIMENTS 1–3

Taken together, our data support the hypothesis that, across tasks, the effect of prior processing events on performance is determined by four key principles (see Fig-

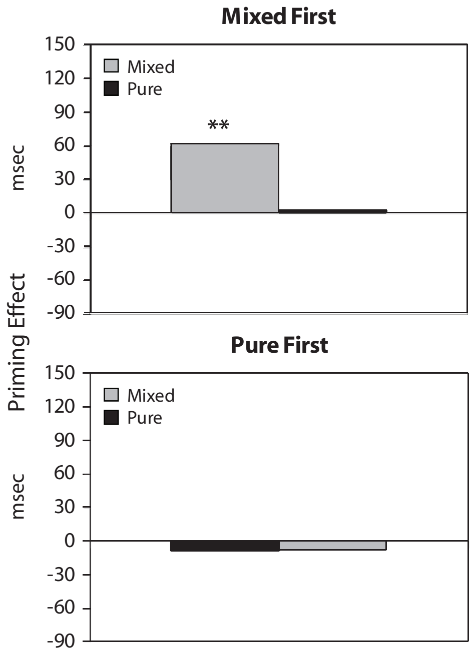

Figure 3. Experiment 3. Priming effect (RT of unprimed items − RT of primed items) separated for 1) pure and mixed blocks, and 2) block order. **$p < .01$, one-tailed t test.

ure 4): First, the longer the *operation time* of the current processing episode, the more probable that a given memory trace influences current processing (Experiments 1–3). Second, the *strength of the association* between stimulus and response determines whether that trace can possibly yield negative priming, in that only strong traces can be retrieved in full, i.e., together with the associated response (Experiment 3). Third, *interference* from a large number of intervening trials of the same task as the probe task obliterates the link between stimulus and response and, thus, turns negative transfer into positive (Experiment 1). Fourth, the effect of *time-based decay* on priming is rather small. Figure 4 illustrates that these factors are able to explain the quite complex pattern of priming effects we observed (in the considerable range from +141 msec to −72 msec!).

We suggest that the probability that a given memory trace influences current processing (regardless of whether or not the trace is fully retrieved) depends, among other things, on the operation time of the current processing episode (see Experiment 4). At a first glance, this notion does not seem to fit to the well-established instance theory of automaticity (Logan, 1988, 1990) which claims that processing is automatic—i.e., fast—when it is based on the retrieval of prior events from memory rather than some general algorithmic computation. However, the instance theory assumes that the decision to rely on memory is based on a race between the retrieval process and the algorithm. Whichever finished first determines performance. Accordingly, performance is automatic (fast) only if there are enough traces stored in memory to win the race. As long as only a few traces are stored, as in the present experiments, memory "wins," i.e., influences performance, only if the algorithm is very slow.

EXPERIMENT 4

A possible reason why the memory trace of a processing episode does not have a unique effect considers the fact that (positive) repetition priming and (negative) cross-task response priming probably involve different mechanisms. The formation of visual object representations has been associated with the temporal synchronization of multiple neural codes in visual cortex in the gamma frequency band (Engel & Singer, 2001). In contrast, synchronization between more distant networks—as necessary for the formation of arbitrary associations between stimuli and responses (e.g., Wise & Murray, 1999)—has been found to use the beta frequency band (Gross et al., 2004;

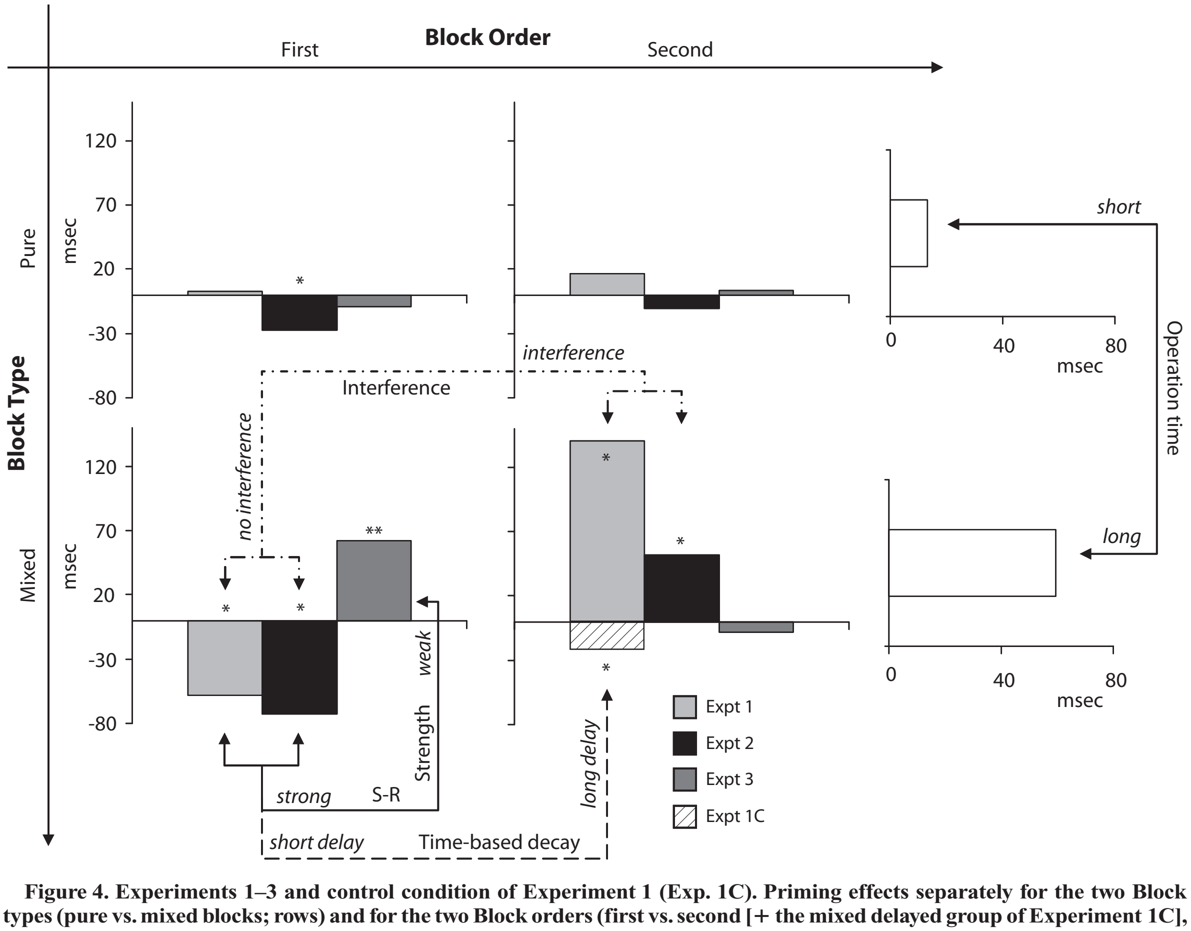

Figure 4. Experiments 1–3 and control condition of Experiment 1 (Exp. 1C). Priming effects separately for the two Block types (pure vs. mixed blocks; rows) and for the two Block orders (first vs. second [+ the mixed delayed group of Experiment 1C], columns). Rightmost column: Absolute priming effects (effect without regard to whether the sign is negative or positive) collapsed across the three experiments and the two lags. See text for details. $^*p < .05$, $^{**}p < .01$, one-tailed *t* tests.

Roelfsema, Engel, Koenig, & Singer, 1997; see Colzato, Erasmus & Hommel (2004) and Colzato, Fagioli, Erasmus & Hommel (2005) for studies exploring the dissociation between stimulus–stimulus and stimulus–response binding mechanisms in more detail).

If one assumes that positive and negative across-task priming is based on mechanisms that are, at least partially, independent of each other, then one would expect the unfolding of positive and negative priming to be sensitive to different aspects of the overall operation time the system needs to produce the response. While positive priming should be sensitive to factors that prolong local integration processes associated with the perception and identification of a stimulus, negative priming should be influenced by factors that prolong the activation of the network responsible for the formation of the link between stimulus and response.

Experiment 4 was meant to explore this issue and, in doing so, to further specify the reason why task switching is so effective in provoking negative across-task priming effects. Experiment 4 assessed once more priming from an AI priming phase to a LS transfer phase. There were two between-subjects conditions, which resulted from the manipulation of operation time: For half of the subjects operation time was prolonged (compared to pure task performance) because they had to switch between the probe task (LS) and the prime task (AI), as in the mixed blocks of the previous experiments. For the other half operation time was prolonged by having a noise mask reducing the stimulus quality of the target pictures. Stimulus quality has been shown to be a powerful determinant of recognition performance (Becker & Killion, 1977; Gilmore, Groth, & Thomas, 2005; Norris, 1984) and it is assumed that the quality of the stimulus affects the rate of feature extraction (Becker, 1976). We assume, thus, that reducing the quality of the targets taps into processes associated with the perception and identification of a stimulus. Task switching, by contrast, prolongs operation time probably because it makes choosing the appropriate task/response more demanding. In the TSI model, for example, (residual) task shift costs are attributed to the prolongation of the response selection stage due to proactive interference from preceding trials performed on the competing task. Accordingly, we assume that switching tasks taps into processes that form the link between stimulus and response.

If these conjectures are correct, then the two ways of prolonging operation time should have different effects on priming: While reducing stimulus quality should boost positive priming, switching tasks should favor the occurrence of negative priming (at least if the association between stimulus and response is strong enough, as already shown in Experiments 1–3).

Method

Forty-four subjects, 14 male and 30 female with a mean age of 22 years, took part for a remuneration of about €7.5. The experiment lasted about 40 min. The method was as in Experiment 1, except that there were two groups of subjects: PURE-LOW and MIXED-HIGH including 20 and 24 participants, respectively. In the transfer phase, the PURE-LOW group performed *pure* blocks in response to pictures presented with a *low* stimulus quality (as shown in Figure 5). The MIXED-HIGH group performed *mixed* blocks in response to *unmasked* pictures. For both groups, the priming phase included six iterations of all stimulus-items of item-set P.

Results

It turned out that eleven items were virtually unrecognizable for most subjects when being masked (PURE-LOW group). These items were excluded from the analysis. (However, this had no influence on the pattern of results.) For the MIXED-HIGH group, overall accuracy was again very high (M = 94.8%, SD = 3.5%). For the PURE-LOW group the accuracy was somewhat lower (M = 87.7%, SD = 4.1%). RTs resulting from erroneous trials were also excluded. The results of the transfer phase of Experiment 4 are illustrated in Figure 5. For comparison, the figure also shows performance in the pure block when presented first taken from Experiment 1 (the bar in the middle). This condition gives an estimate of the priming effect if operation time is not protracted.

An ANOVA was run on the median RTs including the between-participants factor block type (PURE-LOW vs. MIXED-HIGH) and the within-participants factor stimulus set (P vs. U). The only significant effect was the interaction of stimulus set × block type [$F(1,42) = 8.4, p < .01$]. As indicated by the asterisks in Figure 5, one-tailed t tests confirmed the priming effect to be significant for both groups. The same ANOVA run on the error data yielded a significant main effect of block type [$F(1,42) = 43.29$, $p < .001$], with the subjects in the PURE-LOW group committing more errors that the subjects in the MIXED-HIGH

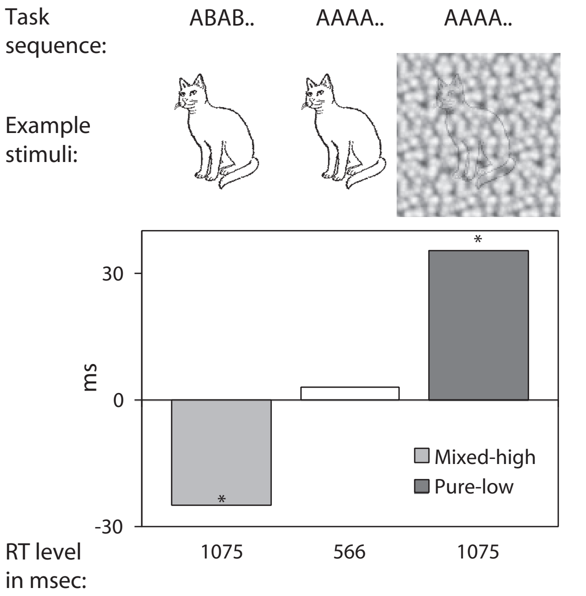

Figure 5. Experiment 4. Priming effect (RT of unprimed items − RT of primed items) separated for the two conditions. Left: MIXED-HIGH: mixed blocks, high stimulus quality. Right: PURE-LOW: pure blocks, low stimulus quality. The bar in the middle shows, for comparison, the pure block/pure first performance of Experiment 1. *$p < .05$, one-tailed t test.

group. This was to be expected since we had to reduce the recognizability of the items presented in the pure-low group strongly in order to equate the RT level between the two groups. However, note that neither the mean RTs nor accuracy in the priming phase (which was identical for both groups) differed between the groups (497 msec vs. 473, $p > .25$; 2.9% vs. 2.8%, $p > .5$), confirming that the two groups are comparable.

Discussion

Figure 5 reveals that both groups showed considerable transfer from the AI priming phase to LS performance in the transfer phase. Most importantly, the transfer was *positive* for the pure-low group and *negative* in the mixed-high group (as in Experiments 1 and 2). Note that these opposed priming effects emerged, even though the overall RT level was exactly the same in both groups (pure-low, 1,075 msec; mixed-high, 1,075 msec).

That is, the pattern of results clearly shows that—in accordance with the reasoning outlined in the introduction of Experiment 4—the two ways of prolonging operation time affect probe trial RTs in a diametrically opposite manner: Providing more operation time by reducing the quality of the stimulus resulted in large positive priming effects. We assume that the low stimulus quality of the target words protracted local integration processes responsible for picture perception and identification. This, in turn, increased the prime events' impact on this "processing stage," resulting in positive repetition priming. Note that the results of the pure-low group amount to a kind of replication of the results of Franks et al. (2000): Positive priming in pure blocks with a rather high overall RT level. We assume, thus, that longer stimulus identification time accounts for the difference between our previous experiments and the study from Franks and colleagues. By contrast, providing more operation time by making subjects switch between two tasks (mixed-high) makes subjects prone to negative across-task transfer effects. It seems, thus, that task-switching is so successful in provoking negative transfer effects, not just because it is one way to delay responses, but because it is a very special way to do so. In particular, we assume that switching tasks hampers the formation of associations between stimuli and responses that depend on synchronizing larger neural networks. In terms of the TSI account (Allport et al., 1994; Wylie & Allport, 2000; Waszak et al., 2003, 2004, 2005), proactive interference from the *preceding* task prolongs the response selection stage of the *current* task. This remaining activation of the competing, currently irrelevant task as a result of trial-to-trial TSI may specifically favor the retrieval of task- and/or response associations consistent with that competing task (if there are associations between stimulus and task/response complied during the priming phase that are strong enough).

Stimulus–Response Versus Stimulus–Task Associations

As mentioned in the introduction, we assume that, during an action event, associations are formed between *all* the encoded constituents, i.e., between stimulus, response, distal goal of the action, task set etc. For brevity, we referred to these links as S–R episodes. The question as to whether the stimulus-driven negative priming observed in the present study is due to the retrieval of *task* representations or individual stimulus–*response* mappings can be tested by comparing priming effects separately for congruent and incongruent stimuli, i.e., for stimuli that map to the same response or to different responses in the two tasks, respectively. To the extent that the priming effect is larger for incongruent than for congruent stimuli it is the retrieval of S–R associations proper that is crucial. If, by contrast, congruent and incongruent stimuli show about the same priming effects, then the priming refers to the task context. Figure 6 shows the priming effects of all conditions in which we observed positive or negative priming, separately for congruent and incongruent stimuli. The only significant difference between incongruent and congruent stimuli was observed in the mixed-high group of Experiment 4 (more negative priming for incongruent than for congruent stimuli). However, an ANOVA with Congruency as a within-subjects factor and Experiment as a between-subjects factor did not yield any significant effect (neither for positive nor for negative priming, all ps $> .2$). As for positive priming, it would at any rate have come as a surprise to find an effect of response congruency. If the positive priming operates on the level of local integration processes associated with the perception of a stimulus, an effect of the associated response is not to be expected, be the response congruent or incongruent.

However, as for the negative priming effects, the present results underscore once more a somewhat more interesting finding already reported by Waszak et al. (2003) and Koch and Allport (2006): if anything, S–R associations proper play only a minor role in negative item-specific cross-task priming. Instead, the effect must be attributed to stimulus-driven priming of higher-order task elements.

GENERAL DISCUSSION

The present study addresses the question as to how performance on a particular set of stimuli transfers from one task context to another. Up to now, two lines of research addressed this question without taking notice of each other. Research on repetition priming and automaticity primarily focused on the consequences of prior presentations in one task context on performance on the same items presented in a different task context. The most straightforward way to do so is to make participants perform two different tasks in two consecutive blocks and to measure the transfer from the first to the second block (AAAAAA . . . BBBBBB . . .). In this tradition of research positive transfer effects were observed (Ellis, et al., 1990; Franks et al., 2000; Logan, 1990, Monsell, 1985; Scarborough et al., 1979). Recently, however, research on executive functions began to investigate the role of priming in task-switching (Waszak et al., 2003, 2004, 2005). This line of research also explores the consequences of priming across two task contexts. However, here the focus is on the consequences of cross-task priming for the participants' ability to switch between the tasks. Accordingly, typical task-switching paradigms were used (AA BB AA BB . . .). In this more recent line of research the cross-task transfer effects turned out to be negative.

The present study is an attempt to bring together these two lines of research. In combining a typical between-block design with a typical task-switching paradigm, we were able to shed some light on the question of why the effects of cross-task priming can be so different. Our study suggests four key principles that can account for cross-task priming effects: First, the longer the *operation time* of the current processing episode, the more likely a given memory trace can influence current processing. Experiment 4 revealed that protracting operation time by reducing stimulus quality favors positive priming effects, whereas providing more operation time by making subjects switch between tasks favors negative priming (if the memory trace can induce negative priming, see second factor!). Second, the *strength of the association* between stimulus and response determines whether that trace can possibly yield negative priming, in that only strong traces can be retrieved together with the associated response. Third, proactive *interference* from intervening trials of the same task obliterates the link between stimulus and response and, thus, turns negative transfer into positive. Fourth, the effect of *time-based decay* on priming is rather small. Moreover, we showed that the cross-task negative transfer must be attributed to stimulus-driven priming of higher-order task elements and not to priming of S–R rules proper.

At a first glance, the results presented in the present paper seem to be in conflict with two aspects of the results reported in the study from Waszak et al. (2003). First, Waszak et al. found that a single picture-naming presentation is sufficient to result in a large negative priming effect in word reading. This seems in conflict with Experiment 3 of the present study, in which a single presentation was insufficient to elicit *negative* priming. However, Waszak et al. used picture–word Stroop stimuli. We speculate that, in Waszak et al.'s experiment, the encoding of the stimulus and the task context during the picture-naming prime trial was "deeper" than in the present study due to the interference of the competing word stimulus. (The system has to overcome the Stroop interference.) This is corroborated by the fact that the picture-naming RTs in the studies from Waszak et al. were between 700 and 900 msec, whereas in the present study, mean RTs of the priming phase were about 500 msec. We assume that the increased processing effort in Stroop picture-naming resulted in a strong stimulus–task/–response association, which, in turn, led to the observed negative priming effects. Admittedly, as far as we know there is no memory theory maintaining that the need to overcome Stroop interference results in particularly strong memory traces. However, it is at least a plausible working hypothesis for future research.

Second, Waszak et al. (2003) report negative priming effects from picture naming on word reading that survive lags of more than 100 intervening picture-naming and word-reading trials. This could be taken to contradict the finding from the present study that proactive interference from the first to the second block as described above reverses the sign of the priming effect. Evidently, the priming effects observed from Waszak et al. might be less prone to proactive interference for much the same reason why they are observed after a single priming trial: simply because the S-response/S-task association is stronger.

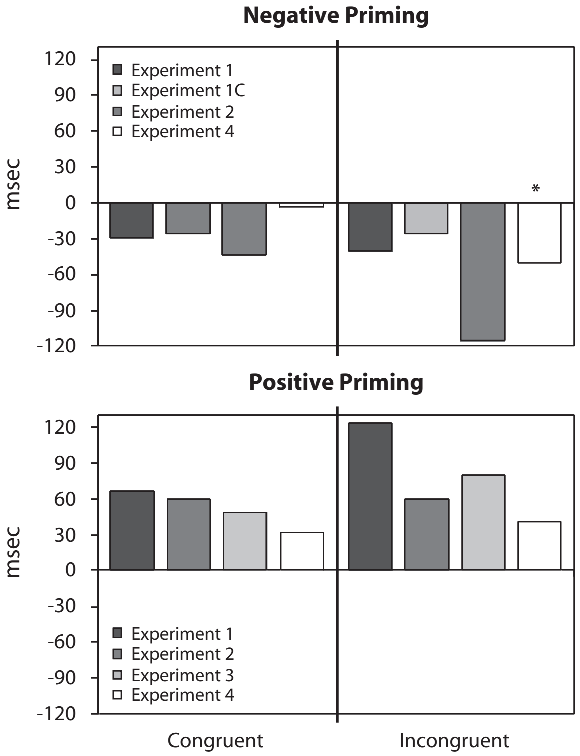

Figure 6. Experiments 1–4. Positive and negative priming effects separately for congruent and incongruent stimuli. Experiment 1C denotes the control condition of Experiment 1. *$p <$ .05, one-tailed *t* test.

AUTHOR NOTE

The authors thank Stefanie Seisenberger for collecting the data. We also thank Gordon Logan (especially for the control condition of Experiment 1), Iring Koch, and an anonymous reviewer for very helpful comments on a previous version of the article. Correspondence concerning this article may be sent to F. Waszak, Laboratoire Psychologie de la Perception, CNRS and Université Paris Descartes, Centre Biomédicale des Saints Pères, 45 rue des Sts Pères, 75270 Paris cedex 06, France (e-mail: f.waszak@gmx.net).

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NOTE

1. There are instances in which negative priming has been observed on switch and repetition trials (see Waszak et al. (2003) and Koch & Allport (2006)). However, in all cases the priming was observed in switch blocks (and not in pure blocks). Under which circumstances negative priming can be observed on switch trials only (increasing shift costs proper) or on switch *and* repeat trials (increasing mixing costs) is an important question in its own right that should be addressed in future experiments. The experiments of the present study do not allow to distinguish between shift and mixing costs.

(Manuscript received September 9, 2005;
revision accepted for publication August 31, 2006.)