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Do stimulus–response bindings survive a task switch?

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Experiencing a single stimulus–response cooccurrence leads to the creation of a binding between the codes of stimulus and response features: an event file. Here we investigate whether event files survive a switch to and from another task (ABBA) or whether task switching involves a suppression of stimulus-response bindings. Participants switched between responding to the colour or the identity of coloured letters, and the mapping of stimuli to response keys varied from trial to trial. Results show that responses were faster if the stimulus in trial matched the stimulus in trial $n-3$, but only if the stimulus–response mapping was repeated. This suggests that stimulus codes were still bound to the codes of the response they accompanied 3 trials earlier and 2 task switches ago. Thus, an event file can survive one or more task switches and, thus, may represent a first step towards a more enduring memory trace.

Pairing a stimulus and a response leads to a strengthening of the association between their internal representations. This is evident not only from everyday experience but also from countless studies on stimulus–response (S–R) learning since the seminal investigations of Pavlov (1927), Thorndike (1927), and others. However, in contrast to these kinds of long-term,

incremental S–R acquisition the present study deals with the representation and learning of single S–R episodes. In particular, it aims at closing a gap between previous demonstrations of long-term aftereffects of experience with a single S–R combination, as reported by Waszak, Hommel, and Allport (2003, 2005), and observations of recency effects of S–R conjunctions (Hommel, 1998b; Hommel & Colzato, 2004; for an overview, see Hommel, 2004).

Waszak and colleagues (2003) had subjects switch between reading the word and naming the picture of Stroop-like word–picture compounds. It turned out that switching to word-reading was more difficult if the particular compound had been picture-named before than if it was only word-read. This was true even if the compound was picture-named only once and if this event preceded the test by more than 100 trials. Further studies in which word and picture components were manipulated separately showed that this episodic effect was not due to any inhibition of the word component during picture-naming. Rather, re-viewing a picture that had been responded to in a particular fashion seemed to prime the apparently associated response, which then created a conflict if another response is required (Waszak et al., 2005). Hence, a single S–R pairing is sufficient to create a rather stable episodic trace that interferes with pairing the same stimulus with another response.

Similar, though not identical conclusions can be drawn from trial-to-trial effects of S–R conjunctions observed by Hommel (1998b). His subjects performed two responses to two stimuli in a row: a fully precued response to the mere onset of the first stimulus (that varied in shape, colour, and location) and a binary-choice response to, say, the shape of the second stimulus (also varying in shape, colour, and location) presented 1 s later. Performance turned out to be impaired if features of the stimulus but not the response were repeated, or vice versa (partial match). This suggests that the mere cooccurrence of a noninformative stimulus and a content-wise unrelated response is sufficient to create an episodic link between them. If either both or none is repeated (complete match and mismatch, respectively), no particular problem arises. However, if one is repeated but not the other, the repeated element will reactivate its linked, now incorrect and misleading, fellow element. Indeed, it can be shown that, in a free-choice task, repeating a stimulus feature increases the likelihood of repeating the previously cooccurring response (Dutzi & Hommel, 2005; Hommel, in press).

It is tempting to take these two kinds of observations to point to the same mechanism. That is, the temporary S–R bindings diagnosed by Hommel (1998b) and colleagues may tap into the microgenesis of an episodic memory process that is responsible for creating enduring S–R traces, such as found by Waszak and colleagues (2003, 2005). Some support for this assumption comes from a recent study of Hommel and Colzato (2004), who

were able to replicate Hommel's (1998b) findings with intervals between the first and the second stimulus (and response) of more than 4 s. And yet, a crucial distinction between the two types of demonstrations remains: Up to now, all experiments demonstrating temporary S–R bindings focused on trial-to-trial effects in pure-block performance. That is, evidence for the existence of temporary S–R bindings has been found primarily in experiments in which effects of (full, partial, and non) S–R overlap between two temporally adjacent trials were tested, without any intervening trials of another, competing task. In contrast, long-term S–R traces have been investigated mainly in task-switching experiments, the reason for this being that Waszak and colleagues (2003, 2005) aimed at showing that a large part of the so-called task shift costs (see, e.g., Meiran, 1996; Rogers & Monsell, 1995) is due to the retrieval of incompatible S–R bindings, created in prior S–R episodes in which the same stimuli occurred in the competing task context. Hence, the large S–R priming effects found by Waszak and colleagues do not only prove that long-lasting S–R traces may guide human performance even more than 100 S–R events later, but they also witness that these memory traces can survive intervening task switches. Accordingly, to corroborate further the notion that enduring S–R traces as demonstrated by Waszak and colleagues are the residues of temporary S–R bindings as shown by Hommel and colleagues, it is necessary to show that temporary S–R bindings, too, outlast a switch of task. In view of the scarcity of data concerning the question as to whether short-term and long-term priming bear on the same mechanisms, this demonstration would be a valuable piece of evidence.

The question is important, the more so as there are reasons to doubt that temporary S–R bindings might survive intervening trials of another task. In task shift experiments, comparing two subsequent task shifts revealed that performance for shifting between only two tasks (ABA) was worse than performance for shifting between three tasks (CBA) (Mayr & Keele, 2000). Accounting for these effects requires two assumptions: First, successfully accomplishing a task shift requires (or at least often involves) inhibiting the previously (preshift) relevant, but currently (postshift) irrelevant task. Second, the inhibition declines—the longer the inhibited task has passed the smaller the inhibition. Hence, accomplishing a previously inhibited task takes longer than accomplishing a noninhibited task. For the lag-2 repetitions (ABA), the previously inhibited task A has to be executed again which has not been fully recovered from the inhibition. Complementarily, the benefit for lag-2 nonrepetitions (CBA) results from absent inhibition of task A. This "backward inhibition" is usually considered to be a means of sequential task-set control: It protects the application of a novel task set by reducing interference from the preceding processing episode. However, the precise mechanism of backward inhibition is still very unclear. For example,

while a study from Schuch and Koch (2003) suggests that backward inhibition does not depend on endogenous preparation, Hübner, Dreisbach, Haider, and Kluwe (2003) found exactly the opposite, that is, that backward inhibition takes place only if subjects endogenously prepare for the upcoming task. More importantly for the present study, there is a paucity of data concerning the question as to what backward inhibition inhibits. Schuch and Koch suggest that it is the whole set of task-specific category– response rules (in their case, odd–left, even–right) that becomes inhibited, because, in their study, the effects could not be explained by the inhibition of more specific aspects of the inhibited processing episode, such as response inhibition or S–R inhibition. However, this should not be taken to mean that Schuch and Koch provided clear-cut evidence that backward inhibition has no effect on S–R episodes. They merely excluded this possibility as a possible explanation for their set of results by preventing, qua design, that switching back to a task is associated with switching back to the same stimulus. It is, thus, by no means excluded that one function of backward inhibition is to inhibit or to tear apart specific S–R bindings, because, in a task-switching context, the continuity of such bindings is counterproductive for the execution of the upcoming task. Hübner and colleagues even speculate that backward inhibition serves to suppress prior S–R processing episodes.

The aim of the present study is thus twofold: First, we want to bridge the gap between short-term and long-term S–R priming effects by showing that short term bindings as shown by Hommel (1998b) and colleagues can survive intervening trials of a different task in a typical task-switching experiment (as it has already been demonstrated for long-term S–R priming; Waszak and colleagues, 2003, 2005). Second, doing so, the experiment explores more precisely the question as to what becomes inhibited in an experiment of sequential task-set control.

Notice that, in usual task switching paradigms (e.g., Meiran, 1996; Rogers & Monsell, 1995), it is impossible to compare subjects' performance in response to complete matches, partial matches, and mismatches between two trials of the same task, as Hommel (1998b) did. This is because, usually, there are fixed S–R rules for a given task, such that a given stimulus always elicits the same response; in other words, there are nothing but complete matches or, in case of a task switch, "complete" mismatches. We devised a new task-switching paradigm that avoids this problem: Using variable stimulus–response mappings—which were cued in advance of each target stimulus—allowed for the independent manipulation of stimulus and response repetitions. This, in turn, made it possible to assess temporary S–R bindings—as diagnosed by the comparison of complete, partial, and mismatches—in a task-switching context.

METHOD

Participants

Forty paid participants served in single sessions. They all reported having normal or corrected-to-normal vision, and were naïve as to the purpose of the experiment. Twenty were assigned to each of the two cue-mode groups (see below).

Apparatus

Participants were seated in a dimly lit room, about 60 cm in front of an Eizo Flexscan screen attached to a Hewlett Packard PC. The experiment was controlled by an experimental software package (ERTS; Beringer, 1995). A wooden board with two response keys was used to record responses. Participants' left and right index fingers rested on the respective left and right keys. Participants pressed one of the keys for classifying a target stimulus.

Task and stimuli

The upper-case letters "X" and "O" in green or red served as target stimuli. The target stimulus appeared in the centre of the screen and subtended $0.9°$ of visual angle both horizontally and vertically.

The task was to classify the colour or the shape of a target stimulus according to an unambiguous but variable stimulus–response mapping (S–R mapping) presented in advance of each target stimulus. Indicating the S–R mapping, the two possible stimulus values of the to-be-classified dimension (e.g., red–green for the colour judgement) were presented on the screen with one stimulus value on the left and the other value on the right side (e.g., green on the left and red on the right side). Participants were instructed to map the left presented stimulus value onto the left key and the right presented one onto the right key and to apply this mapping to the following target stimulus. That is, contrary to conventional task-shifting experiments, symbolic task cues indicating the relevant stimulus dimension such as "perform the shape task" were not applied and subjects did not have to remember predefined and fixed S–R mappings.

For half of the participants (cue-mode group 1), the letters "X" and "O" displayed in grey served as mapping stimuli for the shape task; green and red colour patches were presented for the colour task. Each of these mapping stimuli subtended $0.9° \times 0.9°$. In cue-mode group 2, verbal labels for each stimulus value were presented in German ("eckig" = angular: $0.7° \times 1.4°$;

"rund" =round: $0.5° \times 1.2°$; "grün" =green: $0.7° \times 1.3°$; "rot" =red: $0.5° \times 0.7°$). The centre of each mapping stimulus was $2.5°$ left respective $2.5°$ right from the screen centre.

Procedure

Participants were instructed verbally how to assign mapping stimuli to response keys. They were instructed to react as fast and to make as few errors as possible. Each participant carried out 16 practice trials before the experiment started. The experiment comprised 12 experimental blocks with 65 trials each.

At the beginning of each trial the relevant S–R mapping was presented for 1000 ms. After a blank interval of 500 ms the target stimulus appeared and remained on the screen until the participant pressed a key. Reaction time measured the time between the onset of the target stimulus and the participants' key press. After target stimulus offset the screen went black for 1500 ms before the next trial started. If participants' reaction time was longer than 2000 ms or if participants pressed the wrong key, an error message was shown for 500 ms.

The to-be-classified stimulus dimension changed predictably on every second trial ("alternating runs", Rogers & Monsell, 1995; Spector & Biederman, 1976). Participants performed the shape task twice before they shifted to the colour task and vice versa (A- A- B- B- A-...). Within these task sequences, the S–R mappings were unpredictable and changed randomly from trial to trial.

Design and analysis

Since we focused on within-task transition effects after a switch of tasks, we analysed mapping and stimulus repetitions for lag-3 task repetitions only, that is, transitions from trial $n-3$ to trial n for task shift trials (ABBA).[1] For task shift trials in trial n, the task transition from trial $n-3$ to trial n was a quasi "task repetition" trial, because the to-be-classified stimulus dimension (e.g., colour) was the same. However, the S–R mapping was either repeated or changed (mapping transition). There was a mapping repetition, if the

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[1] We did not consider trial-to-trial transitions of stimuli and responses because the effects of these transitions commonly interact with—and are thus often inflated by—the task-switching factor (Hommel, Pösse, & Waszak, 2000; Pösse, 2001; Rogers & Monsell, 1995). While supporting Waszak et al.'s (2003) claim that stimuli and responses engage in bindings with the task sets they accompany, this characteristic does not allow for a meaningful comparison of the respective outcomes with the longer distance effects of S–R bindings we are interested in.

S–R mapping was identical in trial n and in trial $n-3$ (e.g., green → left and red → right) in both trials. Otherwise, the S–R mapping changed from trial $n-3$ to trial n (e.g., green → left and red → right in trial $n-3$ but green → right and red → left in trial n).

Secondly, the target stimulus was either fully repeated, partially repeated, or alternated (stimulus transition). A stimulus was fully repeated, if in trial $n-3$ and in trial n both stimulus dimensions, colour and form, were the same (e.g., red "X" in both trials). A stimulus was partially repeated, if one stimulus dimension was repeated but the other changed (e.g., green "X" in trial $n-3$ but green "O" in trial n). We did not distinguish between transition on the reaction-relevant stimulus dimension and the transition on the irrelevant stimulus dimension. Finally, there was a stimulus alternation if both stimulus dimensions changed (e.g., green "X" in trial $n-3$ but red "O" in trial n).

RESULTS

After excluding trials with incorrect responses (see Figure 1) and trials that either followed an error (Rabbitt, 1968) or in which the reaction time (RT) was shorter than 100 ms or longer than 2000 ms (8.6% in total), the mean RT and mean error percentage for each experimental condition (stimulus transition x mapping transition) was computed for each participant. Both measures served as input for analyses of variance (ANOVAs), with stimulus transition and mapping transition as within-subject factors, and cue mode as a between-subject factor.

Response times

The ANOVA produced a significant main effect of mapping repetition, $F(1, 38) = 9.01$, $p < .01$, $MSE = 584.84$, indicating that repeating the mapping sped up responses by 10 ms. However, the mapping effect was qualified by stimulus match, $F(1.9, 72.6) = 30.88$, $p < .05$, $MSE = 582.93$. Newman-Keuls post hoc comparisons revealed that the RT in the condition in which mapping and stimulus repetition (475 ms) was significantly smaller than in all other conditions. Hence, the mapping repetition benefit was tied to stimulus repetition ($496-475 = 21$ ms). The main effect of cue mode and interactions involving this factor were not significant.

Errors

The ANOVA revealed also a main effect for mapping transition, $F(1, 38) = 8463$, $p < .01$, $MSE = 5.444$, indicating that participants made fewer errors if
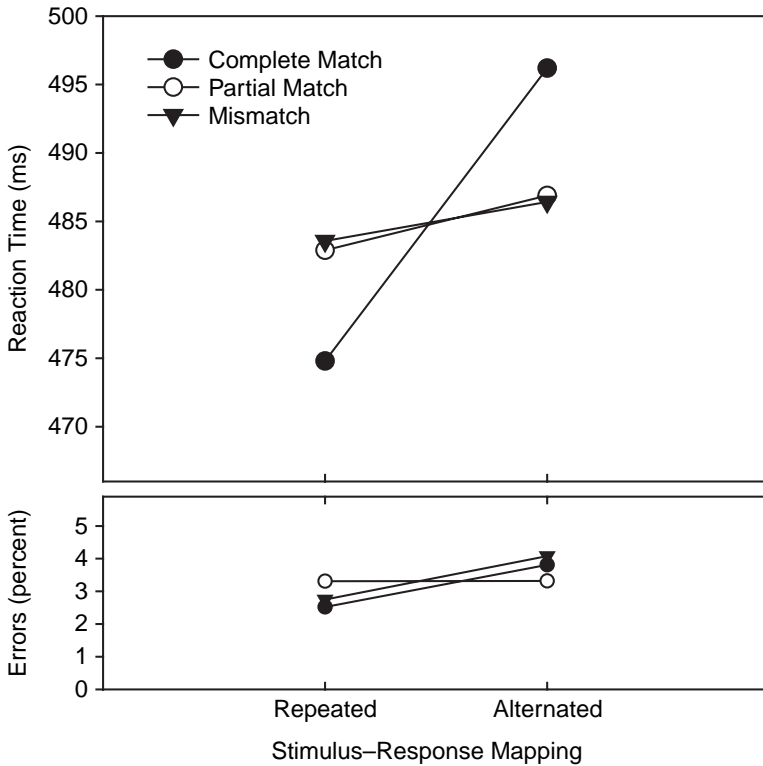
Figure 1. Reaction times and error rates as a function of match between the stimulus in trial n and trial $n-3$, and the repetition versus alternation of S–R mapping.

the mapping was repeated. The second-order interaction of mapping transition and stimulus transition was marginally significant, $F(1.904, 72.349) = 2.580$, $p = .085$, $MSE = 4535$. Newman-Keuls comparisons revealed that the error rate in the condition for mapping and stimulus repetition (2.5%) was significantly lower than in the condition for mapping and stimulus alternation (4.1%) and once again that mapping repetition benefit was tied to stimulus repetition (2.5–3.8% = 1.3%). Cue mode was not involved in any significant effect.

Discussion

The experiment produced two important outcomes. First, a lag-3 repetition of S–R mapping yields faster RTs than a lag-3 switch of S–R mapping and, second, this lag-3 S–R mapping repetition benefit could be observed only for complete lag-3 stimulus repetitions. In other words, performance

improved if the to-be-applied S–R mapping (and, therefore, the to-be-executed response) and the to-be-classified target stimulus were repeated from trial $n-3$ to trial n. This shows that participants profited from associations of stimulus and response features (temporary S–R bindings) although they performed two trials of a competing task in between. The experiment, thus, clearly shows that temporary S–R bindings survive a shift of tasks.

Up to now research on bindings primarily tried to elucidate mechanisms and dynamics of temporary feature integration, for the most part investigated on a trial-to-trial basis in pure-block performance (see, for example, Allport, Tipper, & Chmiel, 1985; Hommel, 1998b; Hommel & Colzato, 2004; Treisman, 1996). Accordingly, there is ample evidence for the existence of some kind of feature integration mechanism that keeps track of which object features goes with which in order to form the representation of an external object (object file, e.g., Allport et al., 1985; Treisman, 1996); there is also ample evidence that codes of the to-be-executed responses can take part in these files, that is, that stimulus features are linked with codes characterising the action to be performed in response to these stimuli (event files or temporary S–R bindings, e.g., Hommel, 1998b).

However, research on bindings has failed yet to demonstrate that temporary S–R bindings are the basis for long-term guidance of perfor-mance, although there is reason to believe that this is the case, as witnessed by long-term effects of the retrieval of integrated S–R episodes (Waszak et al., 2003, 2005). In this context, an obvious question is how stable a temporary binding is, for only a relatively sturdy representation is a possible candidate for a prestage of long-term S–R learning. Hommel and Colzato (2004) demonstrated effects of temporary S–R bindings after 4 s, suggesting that the representation is preserved for a relatively long period of time after the processing event proper. However, if they should pass as a prestage of long-term representations, temporary bindings do not only have to be stable over time, but they also have to be resistant to intrusion of other processes. This is particularly obvious when stimuli do not afford the same response time and again and inhibitory control mechanisms—like backward in-hibition—are necessary to guide subjects' behaviour. A mechanism like backward inhibition, which is thought to shield performance of a novel task (i.e., the execution of a novel reaction in response to an old stimulus) by reducing interference from precedent processing events, may break up links between stimuli and responses that recently were relevant, but that are now irrelevant, and, thus, interfering. The reported experiment demonstrates effects of S–R bindings across a switch of tasks. It is, thus, a first successful attempt to fill the gap between short-term and long-term learning mechan-isms. Evidently, there is still a long way to go and more experiments are needed to bridge the gap completely. For example, Colzato, Erasmus, and

Hommel (2004) were able to show that suppression of the cholinergic activity interrupts temporary feature binding in visual perception, but not across perception and action. To demonstrate that this interruption of associative short-term learning comes along with the collapse of the corresponding long-term bindings would make a strong case for short-term bindings being a prestage for long-term bindings.

Another interesting aspect of the reported results pertains to the question as to what are likely target representations of mechanisms of sequential task control—like backward inhibition. Mayr and Keele (2000) suggest an inhibitory mechanism that works on the level of task set. As long as the inhibition is active, selection of the task set is impaired. Similarly, Schuch and Koch (2003) suggest that that the locus of inhibition is at the level of task-specific category–response rules. However, as pointed out in the introduction, none of these studies directly showed whether backward inhibition tears apart specific S–R bindings. That this is not the case counteracts the assumption that recently abandoned tasks are inhibited as a whole (i.e., the whole S–R rule bundle) and therefore performance is hindered. Instead, participants profited from associations of stimulus and response features, even after the intervening task shift. Admittedly, the effects reported above are not very large and we cannot say whether its small size is due to the mere flow of time between the two events or whether backward inhibition weakens the S–R connections without destroying them completely. Further research is needed to address how the priming effects look like for similar time intervals that are not filled with an alternative task. However, another possible explanation for our findings is that the S–R rule representations that become inhibited are independent from the representations that bring about S–R repetition effects. This interpretation is in line with several ideas discussed in the literature; for example, with the notion that task sets are activated in working memory and that stimulus-cued competition effects are mediated by direct S–R links outside working memory (Hommel, 1998a; Hommel & Eglau, 2002; Mayr & Kliegl, 2000). It is also in line with another idea recently discussed in the task switching literature, namely, that we have to make a distinction between "goal setting" and "task readiness" (Fagot, 1994; Waszak et al., 2003). Setting the goal merely determines which task will be performed (the possible stable states to which the system is able to settle), but it does not affect functional connections, that is, the time the system takes to settle to a task-relevant response. Task readiness, by contrast, is determined in the course of prior processing events (e.g., intentional perceptual-motor actions), which do determine functional connections. Similarly, Hommel and colleagues (Hommel, 1998a; Hommel & Eglau, 2002) distinguished between response activation and response selection. Whereas the former may take place in a stimulus-driven way (e.g., outside working memory through direct S–R

associations), the latter may rely on controlled processing. Backward inhibition may take place on the level of goal setting/response selection, without affecting task readiness/response activation.

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