

Action Planning and the Temporal Binding of Response Codes

Gijsbert Stoet and Bernhard Hommel
Max Planck Institute for Psychological Research

The authors hypothesized that action planning leads to the temporal binding of response codes, which then are less available for the planning of other actions. Four experiments showed evidence for this code occupation hypothesis. In Experiment 1, participants prepared a left or right finger movement (A), performed another left–right choice reaction (B), and then executed Action A. In case of a partial feature overlap between A and B, reaction time for B increased. The same was true in Experiment 2, in which B was performed with the left or right foot. Experiment 3 showed that response-feature binding occurred only when there was sufficient time to form a plan. When A was precued but not intentionally prepared, feature overlap produced a decrease in reaction time. Experiment 4 revealed that A benefited from feature overlap with B at short delays but not at longer delays between B and A. This finding was presumably due to leftover activation in feature codes after plan execution, whereas overlap costs in B were unaffected by delay.

Human behavior is not restricted to simple, immediate, and reflexlike responses to environmental stimuli but most of the time is much better characterized as rather complex, intentional, and goal-directed action. In contrast to reflex-driven behavior, voluntary action is guided, and at least partially controlled, by action plans;¹ that is, cognitive structures assuring that intended action outcomes are actually produced in the intended way. In this article, we ask how such action plans look, how they are formed and maintained, and about the consequences of their formation and maintenance. We assume, like others before us, that actions are planned by recruiting codes that represent and control features of the intended action. We further propose, however, that simply activating those codes does not yet make an action plan. Instead, we claim that action plans are created by temporally associating or binding action-feature codes, an assumption that bears obvious resemblance to the object-file concept proposed by Kahneman and Treisman (1984) in the domain of visual perception. In fact, we argue that an action plan may be thought of as an action file that integrates all the information belonging to an action—very much like an object file integrates the information belonging to a perceptual object.

In the following section, we discuss some theoretical considerations and empirical findings that led us to believe that action-feature integration may play a role in action

planning. Next, we present the outline of a feature-integration approach to action planning and focus on a particularly interesting implication of this approach: the code occupation hypothesis. We describe how we tested the code occupation hypothesis and report four experiments that provide substantial support. However, we begin with the question of how actions are cognitively represented and the implications of their kind of representation.

Distributed Representation of Action and the Binding Problem

Even seemingly simple actions are complex in several ways. First, they usually consist of multiple components. An elementary action such as grasping an object still requires the coordination of finger, wrist, and arm movements and the spatiotemporal coupling of these movements with the goal object (e.g., Jeannerod, 1981; Marteniuk, Leavitt, MacKenzie, & Athenes, 1990), not to mention the coordination with eye movements or body stance. Second, actions have multiple features, some of which may vary though others should not. Whereas the location of a grasping object indicates the action's invariant endpoint and its form and surface characteristics constrain the way it is to be grasped, the object may be reached at various speeds along one of

Gijsbert Stoet and Bernhard Hommel, *Cognition & Action*, Max Planck Institute for Psychological Research, München, Germany.

We wish to thank Fiorenzo Banci and Karl-Heinz Honsberg for constructing the response devices and for technical support; Heidi John for checking and improving the English; and Rich Carlson, Glyn Humphreys, and an anonymous reviewer of a previous draft for helpful comments and suggestions.

Correspondence concerning this article should be addressed to Gijsbert Stoet, who is now at Washington University, School of Medicine, Department of Anatomy and Neurobiology, Box 8108, 660 South Euclid Avenue, St. Louis, Missouri 63110. Electronic mail may be sent to stoet@thalamus.wustl.edu.

¹ Some authors have drawn a conceptual distinction between *motor programming* and *action planning*, the argument being that planning is necessarily more abstract than programming, covers a longer time span, and has a conscious component (e.g., Jeannerod, 1995; Rosenbaum, 1985). However, we are not aware of any theory of action control that would provide sufficiently specific criteria for a clear-cut a priori distinction between a plan and a program in a given task (see Jeannerod, 1997, for a similar argument). Therefore, and because nothing would follow from making this distinction in the present article, we use the terms *plan* and *program* interchangeably, although with a clear preference for the former (theoretically, a more neutral term).

many functionally equivalent movement paths (grasped with one hand or the other, with application of several possible degrees of gripping force, etc.). However, even though some parameters of an action are allowed to vary, they should not be selected randomly but should fit to each other. Third, action control is unlikely to be accomplished by a single, unitary decision center but rather is distributed, both anatomically and functionally. That is, the different features of an action are often specified, and its components organized, by multiple systems located in different brain areas (for overviews see Allport, 1993; Jeannerod, 1997; Keele, Cohen, & Ivry, 1990).

An important common implication of the multiplicity of action components, action features, and action control systems is that they all point to an integration or binding problem. Clearly, coordinated action requires some kind of organization of, or interaction between, different action components or the systems controlling them, but little is known about how this organization is achieved. Singer (1994) discussed two alternative principles to solve this coordination problem on the neuronal level: the command-neuron principle and the temporal-coding principle.

According to the command-neuron principle, the different components of an action plan could be held together by fixed, highly selective connections diverging from a single, high-level command neuron. That is, activating the command neuron would trigger a particular motor program that controls the activity of each individual muscle, much as implied by Keele's (1968) well-known definition of a motor program. As Singer (1994) and Wickens, Hyland, and Anson (1994) have pointed out, though, motor action is unlikely to be organized according to the command-neuron principle for a number of empirical and theoretical reasons, a major one being that no cells showing the required commandlike characteristics have been found so far.

According to the temporal-coding principle, actions are not represented or controlled by a single neuron or code but emerge from the synchronization of activities of a larger number of cells. A given cell, code, or representation does not belong to just one action plan or motor program, but may be involved in the control of many actions. Connections between plan components are not fixed and selective but adjust dynamically to the task at hand, so that actions are controlled by distributed, soft-assembled networks of multifunctional elements. Several authors have proposed that temporal coherence between distributed cells might be established through synchronization of their discharges (e.g., Abeles, 1991; Singer, 1994; von der Malsburg, 1981). An attractive feature of this type of binding mechanism is that it would allow several cell assemblies to be active at the same time, but only if their temporal code is different.

In the literature to date, the discussion of the binding problem and of the temporal-coding principle as a possible solution has been concentrated on perception, especially on the issue of visual object formation (see Treisman, 1996, for a recent overview). The finding that features of visual objects are coded on various feature maps distributed throughout the visual cortex (Cowey, 1985; DeYoe & Van Essen, 1988) has led many researchers to ask how the

cognitive system determines which features belong together. With a cherry tree, for instance, a cherry will be coded as red and round and a leaf, as green and elliptical. If colors and forms are coded on separate maps, how does the system "know" that it is the red object that is round and the green object that is elliptical? Several suggestions have been made of how this feature-binding problem might be solved, and the solutions look rather similar. For instance, a number of psychological models have proposed that visual scenes are scanned serially (e.g., Mozer, 1991; Schneider, 1995; Treisman & Gelade, 1980; Wolfe, 1994), so that information about only one object can be sampled at a time and integrated into a coherent perceptual object structure. In addition, researchers have suggested physiological or physiologically inspired models claiming that this coherence is achieved by the synchronization of cell responses or activity of feature codes (Damasio, 1989; Hummel & Biederman, 1992; Niebuhr, Koch, & Rosin, 1993; Schillen & König, 1994; Singer, 1990), and thereby, in accordance with the temporal-coding principle.

In the domain of action control, however, binding problems have not been an issue in research to date (but see Jeannerod, 1981, 1997, for some related considerations on the integration of perceptual and motor features). A possible reason for this might be that human actors often perform only one action at a time, at least in experimental contexts, and this action is usually not very complex. Imagine, for instance, that an actor is asked to prepare and execute a downward movement with the right hand, such as in a typical key-pressing task. Ignoring the many task-irrelevant movement characteristics (e.g., speed, force, or arm posture) for a moment, we note that performing such an action requires the specification of two action features or movement parameters: hand and direction. Because merely a single movement is required, there is no obvious action-control problem here: All the actor needs to do is to activate the code representing and controlling the right hand (i.e., some *right* code) and the code representing the action feature *downward*; no feature binding seems to be required. But consider what would happen if the actor performed a second movement—an upward movement with the left hand, for example—at the same time. Now, two more codes come into play, one representing the *left* hand and one representing the *upward* feature. Analogous to the cherry tree example, it can now be asked how the action-planning system knows which direction feature belongs to which hand. Obviously, combining two or more actions that have different features and thus require alternative movement parameters creates a very similar problem as is presumably present in the perception of multiple objects.

From Object Files to Event Files

Given the similarity of possible binding problems in object perception and action planning, it is tempting to assume that evolution has provided similar means to solve these problems. This assumption would mean that response features belonging to an action plan are integrated in the same way as stimulus features belonging to the same object,

possibly even by the same mechanism. Support for this assumption comes from the observation that the effects originally taken to be indicative of a binding mechanism in perception generalize to other domains, including those having to do with action.

In perception, first evidence for feature binding came from studies on the negative-priming effect reported by Allport, Tipper, and Chmiel (1985) and others (for reviews, see Fox, 1995; May, Kane, & Hasher, 1995). Typically, this effect occurs if participants respond to the target stimulus of target-distractor pairs, such as a red target letter superimposed on a green distractor letter. If, in a trial, the current target matches the preceding distractor (e.g., red A and green B, preceded by red C and green A), reaction times (RTs) are substantially prolonged, as compared with nonmatch trials (e.g., red A and green B, preceded by red C and green D). According to the interpretation by Allport et al. (1985), revived only recently by Park and Kanwisher (1994), this occurs because the features of target and distractor (i.e., form or identity and color) are integrated separately. If, in a trial, the features combine in the same way as in the preceding trial or if different features are involved, there is no problem. If, however, the same features come up in a different combination, the old bindings have to be undone before the new ones can be formed. Hence, negative priming takes place if features repeat but their conjunctions do not.

Kahneman, Treisman, and Gibbs (1992) found converging evidence for the binding of stimulus features. In their study, participants named single target letters in a probe display that was preceded by a task-irrelevant multiletter preview display. If the same letter appeared in the preview and the probe display, RTs were somewhat, but not much, faster than displays without a match. Repetition effects of this sort are well-known and can be easily attributed to the priming of stimulus feature representations, so-called *type nodes*. Of greater interest, however, the preview benefit largely increased when the matching preview letter appeared in the same (relative or absolute) location as the probe letter. According to Kahneman et al., this occurs because form and location of preview letters were integrated into separate episodic object representations or, in their terms, *object files*. If a probe letter appeared whose form-location combination matched that of a preview element exactly, the object file of this element could be reused so that integration was facilitated or even unnecessary. That is, integration is easier with complete matches than with partial matches.

Originally, Kahneman and Treisman (1984; Kahneman et al., 1992; Treisman, 1992) introduced the concept of an object file as a possible solution to the problem of feature integration and object formation in perception. Although the object-file notion is quite well supported by the available data² (Gordon & Irwin, 1996; Henderson, 1994; Henderson & Anes, 1994; Hommel, 1998), there is converging evidence for the integration of perceptual and motor codes. In neurophysiological investigations of the cat, it has been observed that lever-pressing responses to visual stimuli are mediated by the synchronized firing of cell populations in visual and motor areas, linked through the parietal association cortex (Roelfsema, Engel, König, & Singer, 1997).

Inasmuch as such synchronization processes can be taken to indicate binding (Abeles, 1991; Singer, 1994; von der Malsburg, 1981), this finding indicates that sensorimotor behavior is associated with the binding of sensory and motor codes. In behavioral studies, Hommel (1998b) found that the repetition of a stimulus feature (e.g., form or position) facilitates key-pressing performance only if the response is also repeated; if it is not, stimulus repetition produces a cost. Obviously, stimulus features were getting bound to the response they accompanied, so that presenting the same stimulus feature again reactivated the associated response. Similarly, Danzinger and Robertson (1994) observed that repeating rather than alternating an irrelevant stimulus feature is associated with better performance, but this benefit is more pronounced when the response is also repeated. Altogether, these findings suggest that perceptual and action-related information gets (at least temporarily) integrated into a common episodic representation.

Apparently, effects of feature binding are not restricted to object perception but cross borders between stimulus- and response-feature domains. This implies that the object-file concept introduced by Kahneman and Treisman (1984) is more general than commonly assumed, an implication that led Hommel (1998b) to suggest replacing the concept with the more liberal concept of an *event file*. According to the event-file concept, many or all of the features belonging to an event—whether perceived, produced, or internally generated—might be integrated into a common episodic memory trace, although such a trace will be likely to represent a complex network of distributed local bindings rather than a unitary, single-layered whole (Hommel, 1998b). In the present study, we asked whether event-file formation can also be demonstrated in action planning and, hence, whether binding (i.e., action-file formation) also occurs between the codes of the features belonging to the same response. To implement this, we attempted to translate the experimental logic used in studies on stimulus-feature binding and stimulus-response feature binding into the response domain.

Action Plans and the Code Occupation Hypothesis

Given the empirical evidence for bindings between stimulus features and between stimulus and response features, it is not too farfetched to assume that feature binding also plays a role in action planning and, hence, takes place between response codes.³ That is, making an action plan may involve

² We should add that not all aspects of the object-file approach as held by Kahneman et al. (1992) are equally well supported. For instance, although there is ample evidence that stimulus features are integrated and that integrated structures are accessed by succeeding feature-overlapping stimuli, spatial information seems to play a less dominant role in the access operation than Kahneman et al. have claimed (Hommel, 1998b). However, the usefulness and validity of the object-file concept certainly does not depend on the correctness of particular structural or processable assumptions.

³ Note that we by no means wish to imply that response- or movement-related codes are the only content of an action plan. Quite to the contrary, there are strong reasons to assume that action plans contain information about action goals (e.g., Craighero,

more than just activating the feature components that make up the action, but rather require an integration of these elements into a common episodic structure.⁴

In the present study, we tested the idea of response-feature integration by examining the effects of an already formed action plan held in memory on the formation of another, immediately executed plan. Assume an actor forms the plan to carry out a left-hand action—a movement of the left index finger for example. According to our considerations, this action should lead to the integration of all the features that represent and control the planned action, including the *left* code, representing the hand or finger. Of importance, integration means occupation, and hence, integrated codes are committed to, or associated with, a particular structure. If so, integrated action-feature codes should not be readily available for other planning activities, as long as the current plan is not executed or abandoned. That is, maintaining the plan to perform a *left* action (i.e., an action coded as “left”) should impair the planning of other *left* actions because the *left* code is already occupied by the maintained plan. According to this code occupation hypothesis, any kind of feature overlap or compatibility between a planned and a to-be-performed action should impair performance of the latter.

Note that the code occupation hypothesis follows directly from applying the general idea underlying the object- or event-file concept to the domain of action planning. As the findings from previous studies suggest, feature integration is likely to produce worse performance with partial feature matches between succeeding events, as compared with mismatches. A complete mismatch between action features (see Figure 1, upper row) would be given if, say, some movement is performed with the left hand and another movement, with the right hand. Because the two actions would possess different features, their action plans should not overlap and, thus, should not interfere with each other. Matters are different with a partial match, such as if two different movements are to be carried out with the same hand. At least one element would be shared by the plans of both actions, so that integrating this feature into one plan should make it less available for the other and, hence, impairment of action planning with partial match of action features would occur (cf. Figure 1, lower row).

The Experimental Approach

To test the code occupation hypothesis, we asked participants to perform two tasks in each trial, Task A and Task B (see Figure 2). The most significant feature of our design was that the second task was embedded in the first task. Stimulus A always appeared before Stimulus B, but the

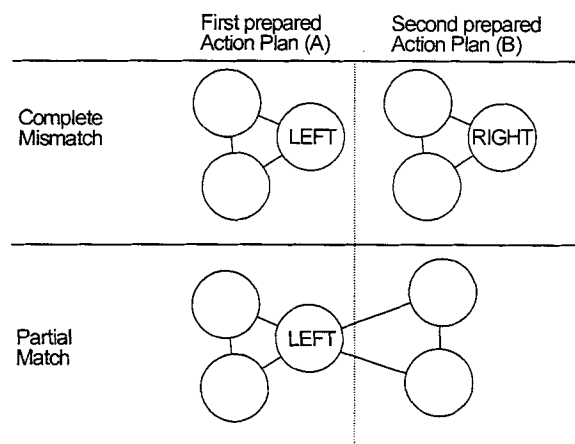


Figure 1. Illustration of two simultaneously active action plans, represented as sets of temporally interconnected response features (circles). In the upper row, the two plans do not share response features, and therefore the construction of the second plan (B) is independent of the first already prepared plan. In the lower row, however, the construction of the second plan (B) requires a feature code that is already integrated into the first action plan (A) and therefore has to be shared by both action plans.

corresponding response had to be executed only after the response to Stimulus B (i.e., Response B) was performed (ABBA design). This implied that the participants were forced to memorize Response A while Task B was performed. Such a design allows for study of the impact of an already formed action plan (the plan to perform Response A) on the efficiency of planning another action (Response B). According to the code occupation hypothesis, planning Response B should be more difficult with feature overlap between the action plans for A and B than without a match. Therefore, we expected RTs for Response B to be higher with A–B overlap—that is, if A and B were to be carried out with the same effector (or with different effectors on the same side)—than with no overlap.

Participants sat before two response panels, one to the left and one to the right of their body midline. On each panel, there were three vertically arranged touch-sensitive metal plates, the central one serving as the home key (at least in Experiment 1; deviations are pointed out in the Method section of Experiments 2, 3, and 4). As shown in Figure 3, Task A was signaled by a left- or right-pointing arrowhead, accompanied by the digit 1 above or below it, or by a 1 and a 2, with the second digit always occupying the location opposite that of the first digit (see the Appendix for an

Fadiga, Rizzolatti, & Umiltà, 1998; Hommel, 1993) and action-relevant stimulus conditions (e.g., Bargh & Gollwitzer, 1994; Goschke & Kuhl, 1993). However, the present study deals exclusively with codes representing the location of actions and with the question of whether and when these codes are bound to an action plan. Therefore, our findings only speak to the issue of response-code binding.

⁴ This hypothesis receives some preliminary support from the single-cell study of Murthy and Fetz (1992), who found that the firing of cell assemblies in the sensorimotor cortex of the monkey gets synchronized when action planning is required (i.e., in a novel and complicated reaching task), but not if the respective task is highly overlearned. If synchronization implies feature binding, this might indicate that the binding of response features is necessary with active planning but not with mere retrieval of an already acquired and stored action plan.

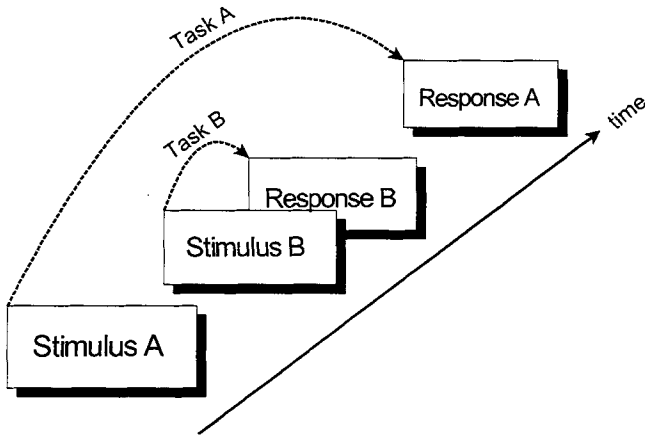


Figure 2. The logic of the ABBA paradigm.

overview of all combinations of stimuli and responses). Arrow direction indicated whether Response A was to be performed with the index finger of the left or right hand. Digits indicated the direction of the response and the number of movement elements. The movement always started with releasing the home key with the hand specified by the arrowhead. Then, the target key corresponding to the location of the numeral 1 had to be touched (i.e., the uppermost key if the digit was above the arrowhead, the lowermost key if it was below). When the numeral 1 appeared alone, participants moved back to the home key and Response A ended. When the numeral 2 was also shown, participants were required to proceed by touching the target key corresponding to the 2 (i.e., the key opposite that of the first digit) and then move back to the home key. Response B was signaled by the presentation of a red or green square, which called for a brief release and retouch of the home key with the left or right index finger (or foot, as in Experiment 2).

Figure 3 shows that after a 350-ms fixation asterisk, Stimulus A was presented for 2 s. This rather long interval gave plenty of time to plan Response A, and participants

were strongly encouraged to do so. Following a 1-s blank interval and another 350-ms fixation mark (this time the outline of the upcoming color stimulus), Stimulus B appeared for 200 ms. It was important that the participant respond to Stimulus B immediately by performing Response B, which was then followed by the already planned Response A.

Experiment 1

We based the first experiment on the design and procedure described above to test the code occupation hypothesis. As a crucial experimental factor, we varied response-feature overlap by asking participants to perform Response A and Response B either with the same hand (and on the same response panel) or with different hands (and on different response panels). We also took care to introduce some degree of response variation by instructing participants to touch either one or two target keys between home key release and retouch and by having them start sometimes with the upper and sometimes with the lower target key position. In doing so, we wanted to verify that participants actually planned Response A on the spot, instead of just retrieving an overlearned action plan from memory. If, for an extreme example, the same Response A was repeated over and over again, participants would be very likely to learn the particular combination of response features and store this combination in long-term memory. Consequently, participants would no longer need to temporally bind the corresponding action codes, and hence form a dynamic action plan, but might simply retrieve the overlearned action pattern as a static whole. If so, binding processes would not be expected to play a major role, so that effects of response overlap might no longer be observed. Therefore, we reasoned that dynamic action planning, the process targeted by our code occupation hypothesis, may only be expected with some degree of response variation, and this variation was realized by varying the number of response elements and the starting position. However, in Experiments 3 and 4 we report that

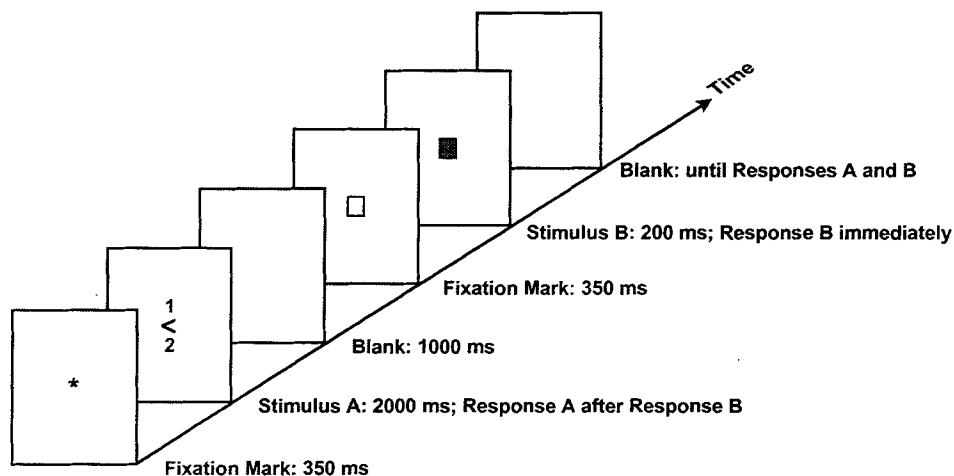


Figure 3. Schematic illustration of the displays and the timing of events in Experiments 1 and 2.

reducing the number of Response A alternatives to two does not change the outcome; therefore, response variation does not seem to play as critical a role as we originally suspected.

Method

Participants. Eighteen volunteers between 18 and 32 years of age were paid for their participation in a single session of about 60 min. Two other participants were excluded because they exceeded the error criterion of 20% overall.

Apparatus and stimuli. The experiment was controlled by a Hewlett Packard Vectra QS20 computer, interfaced with a digital input/output (I/O) card and attached to a 16-in (40.6-cm) Eizo Flexscan monitor. Two wooden boards served as response panels, each supplied with three touch-sensitive metal plates of 1.0×1.0 cm with 0.5 cm in between. A white asterisk on black background served as the first fixation mark that appeared at the center of the monitor. Stimulus A consisted of a white arrow appearing at center screen and the digit 1 plus, if applicable, the digit 2 appearing above and/or below the arrow. From a viewing distance of about 60 cm, each character constituting Stimulus A (i.e., each digit and the arrow) measured about 0.3° in width and 0.4° in height. A white square outline, measuring 0.3° in width and 0.8° in height, was used as the second fixation mark, which also appeared at center screen. Red- and green-filled squares of the same size and location served as Stimulus B.

Design and procedure. There were 16 conditions resulting from the orthogonal variation of four within-participant variables with two levels each: side of Response A (left or right), side of Response B (left or right), complexity of Response A (one or two target keys to be touched), and direction of first movement of Response A (back or forth). Participants worked through a practice block of 32 trials (16 conditions \times 2 replications) and an experimental block of 320 error-free trials (16 conditions \times 20 replications), both blocks randomly ordered (with the constraint that conditions were not immediately repeated). Error trials were recorded and repeated at some random position in the remainder of the block. The two possible mappings of Response B on the color of Stimulus B were counterbalanced across participants.

Following an intertrial interval of 1,250 ms, the order and timing of events was exactly as shown in Figure 3. Participants were instructed to plan Response A as soon as Stimulus A appeared, to wait for Stimulus B and to respond to it as fast as possible, and then to carry out Response A immediately. In case of an error in response type or if the sequence of responses was not completed within 5,000 ms, a brief error message was displayed before the next trial started.

For each response, three measures were taken: For Response B, the first to-be-emitted reaction, RT was measured from the onset of Stimulus B to the first release of the home key, and movement time (MT) was measured from the first release to the following retouch of the home key. RTs and MTs refer to error-free trials only, but percentages of error refer to lifts of the incorrect finger as a proportion of all in-time responses. For Response A, the second reaction, interresponse times (IRTs) were measured from the end of Response B (i.e., the first retouch of the home key) to the second release of the home key; MTs were measured from the interval from the second release to the final retouch of the home key. Error rates for Response A refer to all incorrect in-time responses following a correct Response B. All measures underwent analyses of variance (ANOVAs) for repeated measures, and the significance criterion was set to $p < .05$.

Table 1

Mean Reaction Times (RT), Movement Times (MT), and Interresponse Times (IRT) in Milliseconds and Percentages of Error for Experiment 1 as a Function of Feature Overlap Between Response A and Response B

Condition	Response B			Response A		
	RT	MT	% error	IRT	MT	% error
Overlap	508 (80)	132 (29)	2.0 (1.5)	138 (46)	553 (117)	5.7 (2.1)
No overlap	475 (93)	126 (27)	1.4 (1.3)	153 (50)	576 (134)	6.2 (3.5)

Note. Standard deviations are given in parentheses.

Results

Response B. For each participant, mean RTs, mean MTs, and percentages of error were computed as a function of response-feature overlap (i.e., same vs. different sides of Response A and Response B; see Table 1 for group means). The RT analysis yielded a highly significant effect of overlap, $F(1, 17) = 18.42$, $MSE = 4,314.47$, $p < .001$, indicating that the latency of Response B was longer with overlap between Response B and the prepared Response A than with no overlap. The MTs and error rates showed similar effects that, however, failed to reach significance, $F(1, 17) = 3.87$, $MSE = 606.51$, $p < .07$, and $F(1, 17) = 1.97$, $MSE = 10.27$, $p < .20$, respectively.

Response A. For each participant, mean IRTs, mean MTs, and percentages of error were computed as a function of response-feature overlap (see Table 1 for group means). IRTs and percentages of error did not differ significantly. However, MTs were shorter with feature overlap between Response A and Response B than with no overlap, $F(1, 17) = 7.18$, $MSE = 5,591.41$, $p < .05$.

Discussion

In accordance with our predictions from the proposed code occupation hypothesis, the results clearly demonstrate that feature overlap between a planned and a to-be-performed action negatively affects the latter. First, this was shown in RTs, which indicated that feature overlap with the prepared Response A delayed the initiation of Response B. Second, MTs and errors associated with Response B also increased as a function of feature overlap. Although these effects were not reliable, they were in the same direction as the RT effect, which rules out a possible RT–MT or speed–accuracy trade-off. Rather, the result pattern suggests that the planning of Response B was not always completed when the home key was released, so that some portion of the actual planning-related effect of overlap showed up in MTs. Taken together, the results obtained for Response B provide first, substantial support for the idea that action planning involves the temporal binding of response-feature codes.⁵

⁵ As one of the reviewers pointed out, one may also consider an

Response-feature overlap not only affected the initiation of Response B but the duration and accuracy of Response A as well. We tentatively interpret this result as an aftereffect of response-code activation, the first part of the assumed action-planning process. Assume, for instance, that Response A and Response B are made with the left hand. First, Response A is planned by binding the corresponding response codes together, including the *left* code. If Response B is then to be planned, integrating the *left* code into the new action plan is more difficult, so that the initiation of Response B is delayed. However, as the *left* code was just used for action planning, its activation level may still be above its resting level, so that it might be available somewhat earlier for performing Response A than the unused *right* code. It is true that this would predict a benefit of overlap conditions for RTs and errors but not for MTs; however, if we assume that action planning does not end with the release of the home key, an account of the present MT effect would be tenable. Although we admit that this account is post hoc, we present more evidence supporting it in Experiment 2 and finally put it to test in Experiment 4.

Experiment 2

Experiment 1 showed that action planning is more difficult when the action codes that need to be accessed are already part of another action plan. We call this the cost of response- or action-feature overlap. In Experiment 1, overlap of action codes meant that Response A and Response B were both performed with the same hand. It is this aspect of Experiment 1 that can be taken for an alternative explanation of the observed overlap cost: It might be argued that the longer latencies of Response B in the overlap conditions were the result of some kind of remapping of an effector-specific motor program. According to this argument, planning Response A might result in the construction of a motor program that, in nonoverlap conditions, just needs to be maintained until Response B is completed and then released. With overlap, however, a conflict arises because Response B has to be performed with the same hand as that prepared for by Response A. In order to overcome this conflict, the original plan has to be remapped; that is, it needs to be reprogrammed to allow for the execution of Response B before Response A.

In fact, such a remapping account would not be too different from the binding approach proposed here—after

all, both accounts agree that planning results in some kind of linkage that needs to be undone before a new link can be made. However, it is also obvious that an account of overlap costs in terms of effector-specific motor programs would be much less general and generalizable than the suggested binding approach. Therefore, it seemed important to test whether overlap costs are restricted to feature overlap between actions performed with the same effector or whether effector-unspecific overlap costs are demonstrable.

Experiment 2 replicated Experiment 1 with a slight, but theoretically important, modification: Although Response A was again made with the left or right index finger, Response B was performed with the left or right foot. In the overlap condition, Response A and Response B were performed with hand and foot of the same body side, and in the nonoverlap condition, they were performed with hand and foot of opposite sides.

From a temporal-binding perspective, this modification should not matter, or at least not so much. It is true that the feature overlap of two actions performed with the same effector should be greater than the overlap with two different effectors on the same body side. After all, a left-hand Response A and a left-hand Response B in Experiment 1 do not just share the feature of being made on the *left* side or with the *left* hand; they are also made with the same finger, hand, and arm, start from the same location, and so forth. Many of these features are not shared by responses made with the left hand and the left foot, which limits the degree of feature overlap and, thus, might well reduce overlap costs. Nevertheless, at least some degree of feature overlap should remain, so that substantial overlap costs should be demonstrable even with combinations of hand and foot responses.

From an effector-specific remapping account, however, there is no reason to assume that overlap costs show up if Response A and Response B are performed with different effectors. If, for instance, Response A is prepared for the left foot, remapping would not be necessary, irrespective of whether Response B is made with the left finger or the right finger. Consequently, the disadvantage of overlap observed in Experiment 1 should disappear in Experiment 2.

Method

Participants. Twenty-eight volunteers between 17 and 39 years of age were paid for their participation. Three other participants were excluded because they exceeded the error criterion of 20% overall.

Apparatus and stimuli. The equipment was the same as in Experiment 1, with one exception: For measuring foot responses, two touch-sensitive plates 20×20 cm, mounted on wooden boards 25×40 cm and placed under the participants' feet, were connected to the I/O interface card.

Design and procedure. The procedure was exactly as in Experiment 1, except that Response B was made with the left or right foot, as indicated by the color of Stimulus B. Participants were asked to lift the foot briefly from the touch-sensitive plate and retouch it without lifting the heel.

error-monitor account of overlap costs. Before executing Response B, a hypothetical error monitor might check whether it is really the right plan (i.e., the plan that corresponds to Stimulus B) that was prepared. The monitor might then get "confused" when this plan is the same as the plan for Response A. However, we doubt that such an account is a convincing alternative. First, in the overlap conditions, Responses A and B are by no means the same, they only share some spatial features. Even in Experiment 1, in which the largest overlap costs were obtained, the movement patterns of Response A and Response B were quite different. Second, even if one comes up with a reasonable story of why the monitor gets confused if a to-be-executed and a future action are similar, it is not clear to us why this comparison is made at all.

Results

Response B. Mean RTs, MTs, IRTs, and percentages of error were computed as in Experiment 1 (see Table 2). The effect of response-feature overlap was significant for the RTs, $F(1, 27) = 5.92$, $MSE = 2,832.68$, $p < .05$, which were prolonged if Response B, the foot reaction, was on the same side as Response A, the prepared hand reaction. Likewise, MTs were significantly longer and errors were more frequent with response-feature overlap than with no overlap, $F(1, 27) = 12.83$, $MSE = 54.10$, $p < .001$, and $F(1, 27) = 10.73$, $MSE = 43.50$, $p < .01$.

Additional ANOVAs run on the data from Experiments 1 and 2 confirmed that the 12-ms overlap effect on RTs in Experiment 2 was significantly smaller than the 33-ms effect obtained in Experiment 1, whereas the overlap effects on MTs did not differ.

Response A. IRTs and percentages of error were virtually identical in overlap and no-overlap conditions and, thus, did not differ significantly. However, the MTs were significantly shorter with overlap than with no overlap, $F(1, 27) = 5.09$, $MSE = 457.39$, $p < .05$.

Discussion

The purpose of Experiment 2 was to contrast the code occupation hypothesis, which predicted response-feature overlap costs, with the remapping hypothesis, which predicted no such costs. Although Response A and Response B were always performed with different effectors, clear evidence of performance decrements with feature overlap was found in the RTs, MTs, and percentages of error of Response B. This outcome supports the code occupation hypothesis: Although, as expected, the size of the overlap effect is reduced to that of Experiment 1, its mere occurrence suggests that overlap costs have to do with correspondence or noncorrespondence of response or action features, but less with the identity or nonidentity of the effectors used for Response A and Response B.

Given our tentative account of the Response A-related findings in Experiment 1, it is interesting to note that the present experiment yielded a somewhat similar pattern: It took less time to complete Response A with overlap than with no overlap of Response A and Response B. The

observation that this kind of repetition benefit is replicable, even if different effectors are used for Response A and Response B, rules out possible accounts in terms of anatomical identity or effector activation and, thus, lends additional support to our code activation hypothesis. It appears that using a particular feature code for planning and executing an action leaves some activation for later actions using the same code. In other words, although the occupation of a particular code by a plan seems to end with execution of the planned action, its activation does not.

Experiment 3

The feature-overlap costs observed in Experiment 1 and Experiment 2 provide some initial support for the code occupation hypothesis. However, our evidence that these costs are really due to planning Response A before Response B is still somewhat indirect. Although the participants could not afford to completely ignore Task A until execution of Response B, because Stimulus A was no longer available at the time, participants would not have been able to perform Response A correctly. Moreover, given the rather short latencies of Response A ($IRT < 155$ ms), it certainly makes sense to assume that Response A was prepared before Response B to a considerable degree. However, one may doubt that the short mean IRT alone provides strong enough evidence for the assumption that Response A was prepared before Response B. Perhaps some participants, or occasionally all participants, merely memorized Stimulus A until Response A was to be emitted and only then translated the stimulus into an action plan. If so, some portion of the obtained overlap costs were due to an interaction between Response B and Stimulus A (or some memory code of it) but not to the proposed interplay of Response B and the plan of Response A.

The purpose of Experiment 3 was to test somewhat more directly whether it really is the prepared Response A that interferes with Response B by manipulating the probability that Response A is planned before Response B is prepared and executed. To achieve this goal, we asked participants to complete two different sessions. In a *planning* session, we urged participants to plan Response A before the onset of Stimulus B; as in Experiments 1 and 2, participants had plenty of time to plan. Moreover, we used a less memorizable format of Stimulus A (the arrows were replaced by the letters X and O) to further encourage immediate planning. In a *no-planning* session, run on a different day, we urged participants to plan Response A only after the execution of Response B. Because in this session the stimulus-onset asynchrony between Stimulus A and Stimulus B was just 100 ms and Stimulus A stayed on until Response B was finished, it was not only practically impossible to plan Response A before Response B, but it was unnecessary as well. Obviously, even such an experimental design cannot assure that planning of Response A was always perfect in the planning session and completely absent in the no-planning session. Nevertheless, it does make sense to assume that the degree of planning would be considerably higher in the former session than in the latter session. If so, and if overlap

Table 2
Mean Reaction Times (RT), Movement Times (MT), and Interresponse Times (IRT) in Milliseconds and Percentages of Error for Experiment 2 as a Function of Feature Overlap Between Response A and Response B

Condition	Response B			Response A		
	RT	MT	% error	IRT	MT	% error
Overlap	565 (126)	161 (56)	6.1 (4.3)	155 (63)	581 (149)	4.8 (2.7)
No overlap	553 (115)	158 (56)	4.0 (3.3)	155 (64)	585 (151)	5.0 (3.0)

Note. Standard deviations are given in parentheses.

costs are really produced by the interplay between action plans, we would expect overlap costs to appear in the planning session only, but not in the no-planning session.

Method

Participants. Sixteen volunteers between 17 and 39 years of age were paid to participate in two sessions of about 15 min each, conducted on different days. Three other participants were excluded because they exceeded the error criterion of 20% overall.

Apparatus and stimuli. The same apparatus as in Experiment 1 was used. Task A was signaled by a black uppercase "X" or "O," positioned in a white, filled square on a black background. From a viewing distance of about 60 cm, the letter measured about 0.3° in width and 0.4° in height, and the square subtended 1.0° in width and 2.2° in height. To signal Response B, the square turned green or red. The fixation point and error messages were the same as in Experiment 1.

Design and procedure. There were eight conditions resulting from the orthogonal variation of three within-participant variables with two levels each: side of Response A (left or right), side of Response B (left or right), and planning of Response A (encouraged = *planning*, discouraged = *no planning*). In either session, participants worked through a practice block of 20 trials (4 conditions × 5 replications) and an experimental block of 80 error-free trials (4 conditions × 20 replications). Error trials were recorded and repeated at some random position in the remainder of the block.

In each session, the general method was the same as in Experiments 1 and 2; that is, Stimulus A was followed by Stimulus B, then Response B was performed, followed by Response A (i.e., the ABBA design). Stimulus A, the letter, indicated whether Response A was to be performed with the index finger of the left hand or the right hand. Response A required participants to release the home key, touch the upper target key, touch the home key again, touch the lower target key, and then return to the home key. That is, the complexity and the direction of the first movement of Response A did not vary. Stimulus B and Response B were the same as in

Experiment 1, except that Stimulus B was larger. The two possible mappings of Response A on the identity of Stimulus A, the two possible mappings of Response B on the color of Stimulus B, and the two possible orders of the sessions were all counterbalanced across participants.

In the planning session, each trial started with a white square at the center of the screen (see Figure 4a). After 350 ms, Stimulus A (i.e., a black uppercase "X" or "O") was presented for 1,000 ms at the center of the white square and then disappeared. The square turned green or red 1,000 ms later, indicating the hand with which Response B was to be performed. After another 200 ms, the square turned white again and then completely disappeared as soon as the participant began performing Response A. To encourage the planning of Response A, participants were instructed to perform Response A as quickly and as accurately as possible after completion of Response B. After each 10 error-free trials, visual feedback was given about the mean RT and the number of errors for Response A. An integrated index of performance in Task A was also shown (index of performance = mean IRT + number of errors × 20), including information about improvements relative to the preceding block. The remaining procedural details were the same as in Experiment 1.

In the no-planning session, each trial also started with the onset of a white square at center screen (see Figure 4b). After 1,350 ms, Stimulus A appeared within the square, where it stayed until Response A began. The square signaled Response B 100 ms after the onset of Stimulus A by turning green or red for 200 ms. To discourage the planning of Response A, participants were asked to react as quickly and accurately as possible to the color (i.e., to Stimulus B). Moreover, in contrast to the planning session, the feedback referred to Response B, not Response A. The remaining procedure was the same as in the planning session.

Results

Response B. Mean RTs, MTs, IRTs, and percentages of error were computed as a function of response-feature overlap and planning (see Table 3 for group means). For the

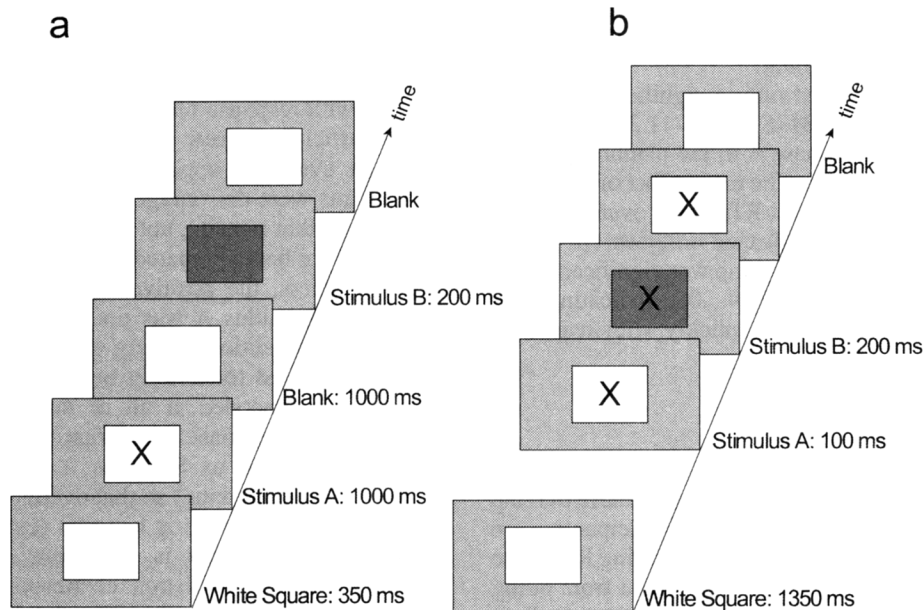


Figure 4. Schematic illustration of the displays and the timing of events in Experiment 3. a: planning session; b: no-planning session.

Table 3
Mean Reaction Times (RT), Movement Times (MT), and Interresponse Times (IRT)
in Milliseconds and Percentages of Error for Experiment 3 as a Function
of Planning and Feature Overlap Between Response A and Response B

Condition	Response B			Response A		
	RT	MT	% error	IRT	MT	% error
Planning						
Overlap	503 (99)	123 (39)	1.6 (2.6)	135 (47)	732 (108)	6.3 (4.7)
No overlap	474 (104)	126 (36)	3.4 (3.2)	157 (59)	741 (111)	8.8 (6.3)
No planning						
Overlap	560 (221)	120 (36)	2.0 (1.8)	280 (129)	774 (114)	6.5 (4.4)
No overlap	595 (225)	125 (36)	5.7 (3.4)	304 (145)	789 (120)	8.6 (5.8)

Note. Standard deviations are given in parentheses.

RTs, only the interaction was significant, $F(1, 15) = 21.46$, $MSE = 1514.68$, $p < .001$, due to the fact that overlap affected RTs negatively in the planning session but positively in the no-planning session. Separate comparisons revealed that both overlap costs in the planning session and overlap benefits in the no-planning session were significant. For the MTs, no significant effects were obtained. The analysis of the percentages of error revealed one significant main effect: Fewer errors were made with overlap than with no overlap, $F(1, 15) = 25.03$, $MSE = 9.56$, $p < .001$.

In contrast to the RTs, overlap and planning did not interact in the error rates, which might indicate some kind of speed-accuracy trade-off. To check this possibility, we computed the product-moment correlation between overlap effect sizes in RTs and percentages of error, separately for each planning session. However, both correlations were far from significance and, if anything, positive in direction (planning: $r = .24$, $p > .4$; no-planning: $r = .03$, $p > .9$), which rules out a trade-off account.

Response A. IRTs revealed only a significant effect of planning, $F(1, 15) = 15.75$, $MSE = 43,711.24$, $p < .001$, with faster initiation of Response A in the planning session than in the no-planning session. The main effect of response-feature overlap, indicating shorter RTs in the overlap condition, only approached the significance criterion ($p < .09$). For the MTs, the main effect of overlap was significant, $F(1, 15) = 7.55$, $MSE = 627.54$, $p < .05$, indicating that Response A was completed more quickly with response-feature overlap than without it.

Discussion

The purpose of this experiment was to determine the role of action planning in producing the response-feature overlap costs observed in Experiments 1 and 2. Participants were encouraged to plan Response A before performing Response B in the planning session but were discouraged from doing so in the no-planning session. Our manipulation worked: Response A was initiated much more quickly in the planning session than in the no-planning session, wherein the IRTs

approached a level that would be expected in a binary-choice task. This result shows that the participants were able to prepare Response A to a much higher degree under conditions that were thought to favor planning processes. The observation that the accuracy of Response B was negatively affected by Response A planning is in the same direction. However, as this may also be an effect of forward masking, due to the shortened interval between Stimulus A and Stimulus B in the no-planning session, we would not like to make too much of it. Nonetheless, there is reason to assume that Response A was planned at least more often or with greater efficiency in the planning session than in the no-planning session.

If it really was the planning of Response A prior to Response B that hampered performing Response B in the overlap conditions of Experiments 1 and 2, we would expect similar overlap costs in the planning session of the present experiment but not in the no-planning session. This is exactly what the results show: Response B was initiated less quickly with response-feature overlap than with no overlap when participants were encouraged to plan Response A, although even the opposite pattern was obtained when participants were discouraged from planning. Obviously, it is planning that matters, not just perceiving or memorizing Stimulus A or being prepared to respond to Stimulus A.

Nevertheless, the positive overlap effect indicated that perceiving Stimulus A was not without any effect in the no-planning condition. Clearly, it is not that Stimulus A was simply presented too briefly before Stimulus B was presented to be encoded at all or to be translated into its corresponding response. Note that we did not use arrowheads, but letters, as Stimulus A (i.e., stimuli with no intrinsic spatial meaning) so that overlap effects can only be attributed to an interaction between (codes of) Response A and Response B. That is, Response A must have been activated before completion of Response B even in the no-planning condition; otherwise, the relationship between Response A and Response B could not have affected performance of Response B. This means that response

(code) activation and response planning are different processes—a conclusion that fits well with our introductory considerations and with recent observations from other dual-task studies, which we cover in the General Discussion.

Experiment 4

In the previous experiments, we found a positive influence of feature overlap on the performance of Response A; that is, MTs for Response A were shorter if the task was performed with the same effector (Experiments 1 and 3) or on the same side of the body (Experiment 2) as Response B. We attributed this overlap benefit to the residual activation of the response codes previously used in the course of planning Response B. Obviously, this interpretation is out of the scope of our code occupation hypothesis and, thus, entirely post hoc. Therefore, we decided to run Experiment 4, which provides an independent test of some implications of the residual-activation interpretation.

It makes sense to assume that an already used action plan is not forever in effect but quickly becomes disintegrated, and it may well be that, as we have considered, the disintegration of a plan precedes the complete deactivation of its elements. Consequently, effects of code activation (i.e., overlap benefits) can be observed even if effects of code integration (i.e., overlap costs) are no longer present. However, even code activation should not stay forever but more or less automatically dissipate after some time (cf., Hommel, 1994), which implies a critical role of the interval between Response B and Response A. In particular, effects of leftover response-code activation should only be observed if the interval between Response B and Response A is short, as was the case in Experiments 1, 2, and 3, but not if the interval is long.⁶

To test this prediction, we manipulated the delay of Response A to Response B by asking participants to carry out the planned Response A only after an auditory *go* signal was presented. In the short-delay condition, we presented the *go* signal about 250 ms after Response B was initiated, so that the relative timing of the responses was very much the same as in Experiments 1, 2, and 3. In the long-delay condition, however, the *go* signal came about 1,250 ms after Response B, so that the two responses were much more separated in time. If feature-overlap benefits were truly due to residual activation of decaying response codes, we would expect those benefits to be present in the short-delay condition but not in the long-delay condition.

Method

Participants. Twenty volunteers age 20 to 30 years were paid for their participation in a single session of about 30 min. One other participant was excluded because he exceeded the error criterion of 20% overall.

Apparatus and stimuli. These were the same as in Experiment 1, with several exceptions. Stimulus A was a centrally presented white letter, "O" or "X," measuring about 0.3° in width and 0.4° in height. Stimulus B was the same as in Experiment 1. Initiation of Response A was signaled by a beep of 50 ms, coming from two loudspeakers positioned at the left and right of the computer screen.

The interval between the initiation of Response B and the beep varied randomly between 200 and 300 ms (a mean of 250 ms) in the short-delay condition and between 1,200 and 1,300 ms (a mean of 1,250 ms) in the long-delay condition.

Design and procedure. There were eight conditions resulting from the orthogonal variation of three within-participant factors with two levels each: side of Response A (left or right), side of Response B (left or right), and delay time (short or long). Participants worked through a practice block of 16 trials (8 conditions \times 2 replications) and an experimental block of 160 error-free trials, both randomly ordered except that immediate repetitions were not allowed. Error trials were recorded and repeated at some random position in the remainder of the block. The two possible mappings of Response B to the color of Stimulus B were counterbalanced across participants.

The timing of events was the same as in Experiment 1, except for the delay between Response B and the *go* signal for Response A. Response B was to be performed 50 to 1,500 ms after the onset of Stimulus B and Response A, within 3,500 ms after the presentation of the *go* signal; otherwise, the trial was aborted and an error message was displayed.

Results

Response B. For each participant, RTs, mean MTs, and percentages of error were computed as a function of response-feature overlap (see Table 4). The RT analysis yielded a significant effect of overlap, $F(1, 19) = 6.46$, $MSE = 1,365.58$, $p < .05$, indicating that the latency of Response B was longer with overlap between Responses B and A. Neither the MT nor the percentage of error analyses of Response B yielded significant effects.

Response A. RTs were measured from the onset of the *go* signal to the initiation of Response A. The RT analysis yielded a significant effect of overlap, $F(1, 19) = 8.12$, $MSE = 876.97$, $p < .01$, indicating that the latency of Response A was shorter with overlap between Response B and Response A. There was a significant effect of delay, $F(1, 19) = 48.62$, $MSE = 21,649.81$, $p < .001$, due to the fact that RTs were shorter when the delay between Responses B and A was longer. Most important, a significant interaction between delay and overlap, $F(1, 19) = 10.11$, $MSE = 5252.06$, $p < .005$, indicated that the feature-overlap benefit was significant in the short-delay condition but not with long delays, which was also confirmed in separate analyses.

The MT analysis revealed a significant effect of delay, $F(1, 19) = 33.40$, $MSE = 683.42$, $p < .001$, showing that MTs in the short-delay condition were shorter than in the long-delay condition. The percentage of error analysis yielded no significant effects.

Discussion

The results were as expected. Apart from another replication of the feature-overlap costs associated with Response B,

⁶ It is important to point out that the binding account does not predict negative effects of feature-overlap on Response A. Negative effects of feature overlap are expected to appear only when codes have to be bound: Because Plan A has been bound before Plan B was constructed, there is no reason to expect binding problems after the execution of Response B.

Table 4
Mean Reaction Times (RT), Movement Times (MT), Interresponse Times (IRTs), in Milliseconds and Percentages of Error for Experiment 4 as a Function of Feature Overlap Between Stimulus A and Response B and Delay of Response A

Condition	Response B			Response A		
	RT	MT	% error	IRT	MT	% error
Short delay						
Overlap	410 (70)	110 (31)	2.0 (2.0)	303 (68)	776 (121)	6.9 (4.8)
No overlap	399 (59)	111 (35)	1.5 (2.1)	332 (71)	776 (117)	6.5 (4.7)
Long delay						
Overlap	412 (69)	110 (30)	2.5 (2.8)	247 (65)	802 (130)	7.3 (4.3)
No overlap	394 (48)	112 (32)	2.5 (2.7)	244 (67)	797 (126)	7.6 (4.2)

Note. Standard deviations are given in parentheses.

the overlap benefit observed in Response A was clearly dependent on the delay between the two responses.⁷ If the delay was about as short as it was in the previous experiments, feature overlap produced a substantial benefit for Response A—the size of this effect was even stronger than in Experiments 1 and 3. However, if the delay was long, there was not the slightest indication of any effect of overlap. This provides further independent evidence for the assumption of two different and successive phases of action-plan deactivation: disintegration and decay.

General Discussion

The main purpose of the experiments reported in this article was to find out whether action planning is associated with a feature-binding problem. We discussed arguments for why such a problem might exist and presented an account of how it may be solved. From this, we then derived what we call the code occupation hypothesis, which we tested by using a novel dual-task method with one action embedded between planning and executing another action. In accordance with our hypothesis, Experiment 1 showed that planning an action is impaired if it shares features with another, already planned action plan held in memory. Experiment 2 indicated that feature-overlap costs can be found even if the overlapping features do not refer to the same effector (i.e., when overlap is fairly abstract). Experiment 3 demonstrated in a more direct way that feature-overlap costs depend on intentional planning. If an action overlaps with a cued but not intentionally prepared action plan, it is no longer interfered with; if anything, it is facilitated. In Experiment 4 we studied whether and how carried-out action plans can affect subsequent actions. The results suggest that although action plans quickly disintegrate after execution, their elements (i.e., response-feature codes) may still be activated for some time, thereby facilitating the performance of feature-overlapping actions. However, this activation does not last very long and decays after about 1 s or less. Our findings have a number of theoretical implications, which we now discuss in turn.

Feature Binding as a General Principle in Cognitive Representation

In our view, the overlap costs we observed when a to-be-performed action shares features with an already constructed action plan reflect a binding conflict: Planning an action involves the integration of, or binding between, those action features that specify the intended action (or action effect), so that the bound feature codes are temporarily not readily available for the planning and control of other actions. Although the finding of overlap costs in the action domain is new, it fits well with a number of previous observations of (as we believe) similar effects in other domains.

First, stimulus-feature overlap costs have been observed in negative-priming tasks (e.g., Allport et al., 1985) and with preview designs (e.g., Hommel, 1998b). As discussed earlier, the evidence available to date shows that a partial match between the features of succeeding stimuli produces a worse performance than a complete mismatch. In other words, feature overlap between two event representations formed in close temporal succession impairs performance, as compared with no overlap (as we demonstrated for action events).

Second, overlap costs have also been found with stimulus-response pairings, as in the study of Hommel (1998b).

⁷ As confirmed by an ANOVA across experiments, the costs of feature overlap tended to be smaller in Experiment 4 than in Experiment 1, $F(1, 36) = 3.68$, $MSE = 1,598.19$, $p < .07$. Our hunch is that this drop is due to the lesser variability in Response A planning in Experiment 4, in which only two Response A alternatives were used, as compared to Experiment 1, with its eight alternatives. As we discussed in Experiment 1, using the same plan over and over again may lead to the storage of an integrated representation of this plan in long-term memory, which can then be retrieved without further planning if required. High trial-to-trial variability of action planning can be assumed to work against the formation of such a representation and, thus, increase demands on on-line action planning.

Again, a partial match between a particular combination of stimulus and response features produces a worse performance than a complete mismatch. This suggests that stimulus and response features are integrated into a common representation, so that the features involved are temporarily not readily available for the formation of other representations.

Third, recent findings of Müsseler and colleagues demonstrate that feature overlap between an about-to-be-performed manual action and a to-be-identified visual stimulus impairs perceiving the latter. Müsseler and Hommel (1997a, 1997b) showed that identifying or detecting an arrow pointing to the left or right is more difficult if it appears at about the same time a spatially compatible response is made, such as pressing a left or right response key. According to our account, this is because the *left* or *right* code is occupied by the to-be-executed action plan (i.e., pressing the left or right response key) at the moment it would be required for coding the left- or right-pointing arrowhead.⁸ In fact, Wühr and Müsseler (1997) observed that “blindness” to response-compatible stimuli can set in as early as 2 s before the planned manual response is actually emitted, showing that it is not the execution but the planning of a feature-overlapping action that hampers perception. Once again, forming a representation of a perceived or to-be-performed event impairs the formation of other representations involving the same features.

All of this research demonstrates that feature binding is not restricted to stimulus features, as originally assumed (e.g., Kahneman & Treisman, 1984), but can be observed among response features and between stimulus and response features as well. Both perceived stimulus objects and planned actions seem to be represented by integrated bundles of feature codes, and even higher order representations of stimulus–response combinations seem to be formed spontaneously. Taken altogether, this strongly suggests that feature binding is a fairly general principle to form and organize cognitive event representations. Nevertheless, there are also indications for some important differences between stimulus and action representations.

Response-related costs of feature overlap, on the one hand, seem to be bound to active planning, as shown in Experiment 3, and are rather short-lasting. The latter is indicated by both Wühr and Müsseler’s (1997) observation that difficulties in perceiving response-compatible stimuli disappear as soon as the overlapping response is executed and our own finding that overlap costs are confined to Response B but do not occur in the following Response A. Apparently, planning an action is associated with feature binding, but the respective feature codes are released and are then available for other bindings soon after the action plan is realized.

Stimulus-related overlap costs, on the other hand, seem to be due to automatic processes and are rather long-lasting. Obviously, the mere presentation of a task-irrelevant stimulus—as in Kahneman et al.’s (1992) original preview design or in Hommel’s (1998b) adaptation—is sufficient to cause overlap costs in perceptual processes that run off 1s (or more) later. The same is true for coincidental stimulus–

response conjunctions, in which automatically formed representations are stored for at least 1 s (Hommel, 1998b). These findings suggest that the binding of perceptual features (with other perceptual or action features) is much more automatic than the binding of action features (with other action features), at least if (and perhaps because) the feature-possessing stimuli are perceptually available. Moreover, the integrated event representations are maintained for a much longer period of time for perceptual than for pure action events. Clearly, this is an important difference that deserves further investigation.

Abstract Coding of Action Plans

An important question about action planning concerns the level of abstraction on which the basic components of action plans are defined. According to Keele (1968), a motor program is a structured set of muscle commands—a relatively concrete and peripheral entity. Later approaches, such as Rosenbaum’s (1985, 1987), have assumed that programs are built from abstract codes—from movement parameters that need not directly map on specific muscle commands. Although the present study did not aim to answer this question, its outcome supports the assumption that abstract codes are involved in action planning. In Experiment 2, we saw that planning a left- or right-hand action hampers foot responses on the same side of the body. That is, body side or egocentric location of the effectors must have been coded in the corresponding action plans independently of the effector’s identity, which clearly rules out the idea that planning occurs in terms of muscle commands.

Our findings fit well with other observations that also point to the abstract nature of action planning. For instance, Rosenbaum and colleagues have repeatedly shown that the time it takes to plan manual actions decreases with the amount of advance information the actor receives about abstract, outcome-related action features (see Rosenbaum, 1987, for an overview). That is, action plans seem to take abstract parameters. In the same vein, Ulrich, Moore, and Osman (1993) found that actions can be planned up to the level of a measurable lateralized readiness potential (LRP), even if the actual effector is not yet known. In their experiment, participants were given advance information about the hand of an upcoming manual action but not about the finger to be moved, so that the information was too abstract to allow for preparing a specific set of muscles. Yet, partial information about the hand significantly speeded up LRP onset, suggesting that the LRP reflects the implementation of abstract response parameters.

A Two-Process Approach to Action Planning

According to the common view, the gap between stimulus processing and action control is bridged by a single process, usually called *stimulus–response translation* or *response*

⁸ Here we presuppose that the same codes are used for coding the location of a stimulus and the location of an action—an assumption that finds ample support from studies on stimulus–response compatibility (see Hommel, 1997; Müsseler & Hommel, 1997a).

selection (e.g., Meyer & Kieras, 1997; Sanders, 1990; Teichner & Krebs, 1974; Theios, 1975). The basic assumption underlying most current models of human information processing is that after the stimulus is analyzed to at least some degree, some kind of selection process is called or some automatic translation device is activated, which then assures that the correct motor program is launched.

However, this single-step translation view has been challenged by a study of Hommel (1998a), who was working with a standard dual-task design involving a primary manual key-pressing task and a secondary vocal color-naming task. On the one hand, secondary-task performance decreased as the time interval between primary and secondary stimulus shortened; hence, it decreased with increasing temporal task overlap. Of course, such an outcome is hardly surprising and merely replicates the well-known finding that people are unable to select two responses at the same time (see Pashler, 1994, for a recent overview). On the other hand, however, the compatibility between the secondary response (the word *red* or *green*) and the primary stimulus (a red or green color patch) strongly affected primary task performance. This finding shows that the secondary response was activated before the primary task was completed and, thus, suggests that stimulus-response translation does not provide a bottleneck in dual-task performance. To account for this pattern of results, Hommel (1998a) suggested distinguishing between response *activation*, which typically results from stimulus-response translation, and eventual response *selection*, which involves recruiting those already activated response codes that belong to the same response.

Our present findings fully support and extend this two-process view of response determination. For all conditions in which participants were encouraged to plan Response A, we found a substantial impairment of compatible B responses—an effect we attribute to the binding of response features in the process of planning Response A. If planning was neither encouraged nor likely, as in the no-plan condition of Experiment 3, we found a positive compatibility effect. This result is exactly what one would predict if stimulus-response translation and the resulting activation of response features were automatic, as Hommel (1998a) assumes. Therefore, we conclude that action planning consists of two processes or stages: an automatic one, responsible for activating those action-feature codes that are signaled by the stimulus, and another, more effortful one that binds the activated features. That is, constructing an action plan requires not just specifying the features of the intended action but also temporarily binding them to form an integrated whole. Of interest, the dissipation of action plans seems to reflect the way they emerge, with the disintegration or unbinding of feature codes being followed by their deactivation.

In summary, the present findings provide substantial evidence for the idea that feature-binding mechanisms may be operative not only in perception but in action planning as well, suggesting that they play a major role in the cognitive coding of perceived and produced events. Future research is required to investigate the apparently different characteristics of pure action-related bindings and those involving

stimulus codes. It would also be of importance to know whether and how the binding of stimulus features affects or interacts with the binding of action features. We have already begun to tackle these issues, and preliminary results suggest that the experimental design introduced in this article may be of some help in this enterprise. Further research is also necessary to find out whether binding effects can only be observed with spatial response features (which we focused on in this study) or whether other features (e.g., temporal) are associated with comparable phenomena.

References

- Abeles, M. (1991). *Corticonics: Neural circuits of the cerebral cortex*. Cambridge, England: Cambridge University Press.
- Allport, D. A. (1993). Attention and control: Have we been asking the wrong questions? A critical review of twenty-five years. In D. E. Meyer & S. Kornblum (Eds.), *Attention and performance XIV* (pp. 183–218). Cambridge, MA: MIT Press.
- Allport, D. A., Tipper, S. P., & Chmiel, N. R. J. (1985). Perceptual integration and postcategorical filtering. In M. I. Posner & O. S. M. Marin (Eds.), *Attention and performance XI* (pp. 107–132). Hillsdale, NJ: Erlbaum.
- Bargh, J. A., & Gollwitzer, P. M. (1994). Environmental control of goal-directed action: Automatic and strategic contingencies between situations and behavior. In W. D. Spaulding (Ed.), *Nebraska Symposium on Motivation: Vol. 41. Integrative views of motivation, cognition, and emotion* (pp. 71–124). Lincoln: University of Nebraska Press.
- Cowey, A. (1985). Aspects of cortical organization related to selective attention and selective impairments of visual perception: A tutorial review. In M. I. Posner & O. S. M. Marin (Eds.), *Attention and performance XI* (pp. 41–62). Hillsdale, NJ: Erlbaum.
- Craighero, L., Fadiga, L., Rizzolatti, G., & Umiltà, C. (1998). Visuomotor priming. *Visual Cognition*, 5, 109–125.
- Damasio, A. R. (1989). The brain binds entities and events by multiregional activation from convergence zones. *Neural Computation*, 1, 123–132.
- Danzinger, S., & Robertson, L. C. (1994, May). *Repetition effects of response irrelevant features*. Poster session presented at the 35th annual meeting of the Psychonomic Society, St. Louis, MO.
- DeYoe, E. A., & Van Essen, D. C. (1988). Concurrent processing streams in monkey visual cortex. *Trends in Neuroscience*, 11, 219–226.
- Fox, E. (1995). Negative priming from ignored distractors in visual selection: A review. *Psychonomic Bulletin & Review*, 2, 145–173.
- Gordon, R. D., & Irwin, D. E. (1996). What's in an object file? Evidence from priming studies. *Perception & Psychophysics*, 58, 1260–1277.
- Goschke, T., & Kuhl, J. (1993). The representation of intentions: Persisting activation in memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 19, 1211–1226.
- Henderson, J. M. (1994). Two representational systems in dynamic visual identification. *Journal of Experimental Psychology: General*, 123, 410–426.
- Henderson, J. M., & Anes, M. D. (1994). Roles of object-file review and type priming in visual identification within and across eye-fixations. *Journal of Experimental Psychology: Human Perception and Performance*, 20, 826–839.
- Hommel, B. (1993). Inverting the Simon effect by intention: Determinants of direction and extent of effects of irrelevant spatial information. *Psychological Research/Psychologische Forschung*, 55, 270–279.

- Hommel, B. (1994). Spontaneous decay of response code activation. *Psychological Research/Psychologische Forschung*, 56, 261–268.
- Hommel, B. (1997). Toward an action-concept model of stimulus-response compatibility. In B. Hommel & W. Prinz (Eds.), *Theoretical issues in stimulus-response compatibility* (pp. 281–320). Amsterdam: North-Holland.
- Hommel, B. (1998a). Automatic stimulus-response translation in dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, 24, 1368–1384.
- Hommel, B. (1998b). Event files: Evidence for automatic integration of stimulus-response episodes. *Visual Cognition*, 5, 183–216.
- Hummel, J. E., & Biederman, I. (1992). Dynamic binding in a neural network for shape recognition. *Psychological Review*, 99, 480–517.
- Jeannerod, M. (1981). Intersegmental coordination during reaching at natural visual objects. In J. Long & A. Baddley (Eds.), *Attention and Performance IX* (pp. 153–168). Hillsdale, NJ: Erlbaum.
- Jeannerod, M. (1995). Mental imagery in the motor cortex. *Neuropsychologia*, 33, 1419–1432.
- Jeannerod, M. (1997). *The cognitive neuroscience of action*. Cambridge, MA: Blackwell.
- Kahneman, D., & Treisman, A. (1984). Changing views of attention and automaticity. In R. Parasuraman & D. R. Davies (Eds.), *Varieties of attention* (pp. 29–61). Orlando, FL: Academic Press.
- Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files: Object-specific integration of information. *Cognitive Psychology*, 24, 175–219.
- Keele, S. W. (1968). Movement control in skilled motor performance. *Psychological Bulletin*, 70, 387–403.
- Keele, S. W., Cohen, A., & Ivry, R. (1990). Motor programs: Concepts and issues. In M. Jeannerod (Ed.), *Attention and performance XIII: Motor representation and control* (pp. 77–110). Hillsdale, NJ: Erlbaum.
- Marteniuk, R. G., Leavitt, J. L., MacKenzie, C. L., & Athenes, S. (1990). Functional relationships between grasp and transport components in a prehension task. *Human Movement Science*, 9, 149–176.
- May, C. P., Kane, M. J., & Hasher, L. (1995). Determinants of negative priming. *Psychological Bulletin*, 118, 35–54.
- Meyer, D. E., & Kieras, D. E. (1997). A computational theory of executive cognitive processes and multiple-task performance: Part 1. Basic mechanisms. *Psychological Review*, 104, 3–65.
- Mozer, M. C. (1991). *The perception of multiple objects: A connectionist approach*. Cambridge, MA: MIT Press.
- Murthy, V. N., & Fetzi, E. E. (1992). Coherent 25- to 35-Hz oscillations in the sensorimotor cortex of awake behaving monkeys. *Proceedings of the National Academy of Science USA*, 89, 5670–5674.
- Müsseler, J., & Hommel, B. (1997a). Blindness to response-compatible stimuli. *Journal of Experimental Psychology: Human Perception and Performance*, 23, 861–872.
- Müsseler, J., & Hommel, B. (1997b). Detecting and identifying response-compatible stimuli. *Psychonomic Bulletin & Review*, 4, 125–129.
- Niebuhr, E., Koch, C., & Rosin, C. (1993). An oscillation-based model for the neuronal basis of attention. *Vision Research*, 33, 2789–2802.
- Park, J., & Kanwisher, N. (1994). Negative priming for spatial locations: Identity mismatching, not distractor inhibition. *Journal of Experimental Psychology: Human Perception and Performance*, 20, 613–623.
- Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin*, 116, 220–244.
- Roelfsema, P. R., Engel, A. K., König, P., & Singer, W. (1997). Visuomotor integration is associated with zero time-lag synchronization among cortical areas. *Nature*, 385, 157–161.
- Rosenbaum, D. A. (1985). Motor programming: A review and scheduling theory. In H. Heuer, U. Kleinbeck, & K.-M. Schmidt (Eds.), *Motor behavior: Programming, control, and acquisition* (pp. 1–33). Berlin: Springer-Verlag.
- Rosenbaum, D. A. (1987). Successive approximations to a model of human motor programming. *The Psychology of Learning and Motivation*, 21, 153–182.
- Sanders, A. F. (1990). Issues and trends in the debate on discrete vs. continuous processing of information. *Acta Psychologica*, 74, 123–167.
- Schillen, T. B., & König, P. (1994). Binding by temporal structure in multiple feature domains of an oscillatory neuronal network. *Biological Cybernetics*, 70, 397–405.
- Schneider, W. X. (1995). VAM: A neuro-cognitive model for visual attention control of segmentation, object recognition, and space-based motor action. *Visual Cognition*, 2, 331–376.
- Singer, W. (1990). Search for coherence: A basic principle of cortical self-organization. *Concepts in Neuroscience*, 1, 1–26.
- Singer, W. (1994). The organization of sensory motor representations in the neocortex: A hypothesis based on temporal coding. In C. Umiltà & M. Moscovitch (Eds.), *Attention and Performance XV: Conscious and nonconscious information processing* (pp. 77–107). Cambridge, MA: MIT Press.
- Teichner, W. H., & Krebs, M. J. (1974). Laws of visual choice reaction time. *Psychological Review*, 81, 75–98.
- Theios, J. (1975). The components of response latency in simple human information processing tasks. In P. M. A. Rabbitt & S. Dornic (Eds.), *Attention and performance V* (pp. 418–440). London: Academic Press.
- Treisman, A. (1992). Perceiving and re-perceiving objects. *American Psychologist*, 47, 862–875.
- Treisman, A. (1996). The binding problem. *Current Opinion in Neurobiology*, 6, 171–178.
- Treisman, A., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, 12, 97–136.
- Ulrich, R., Moore, C., & Osman, A. (1993). Lateralisiertes Bereitschaftspotential und Reaktionsgeschwindigkeit bei partieller Vorinformation eines Handlungsparameters [Lateralized readiness potential and reaction speed with partial preinformation of an action parameter]. *Zeitschrift für Experimentelle und Angewandte Psychologie*, 40, 310–325.
- von der Malsburg, C. (1981). *The correlation theory of brain function* (Internal report). Göttingen, Germany: Max-Planck Institute for Biophysical Chemistry.
- Wickens, J., Hyland, B., & Anson, G. (1994). Cortical cell assemblies: A possible mechanism for motor programs. *Journal of Motor Behavior*, 26, 66–82.
- Wolfe, J. M. (1994). Guided search 2.0: A revised model of visual search. *Psychonomic Bulletin and Review*, 1, 202–238.
- Wühr, P., & Müsseler, J. (1997). *Time course of the blindness to response-compatible stimuli* (Paper 2). München, Germany: Max-Planck Institute for Psychological Research.

Appendix

Description of the Possible Stimuli and Responses for Each Level of Experiment 1 and Experiment 2

Variable				Stimulus		Response	
Side of Response A	Side of Response B	Complexity	Direction of first movement	A	B	B	A
Left	Left	Low	Up	1	red	left (home)	left (up-home)
			Down	< 1	red	left (home)	left (down-home)
		High	Up	1 < 2	red	left (home)	left (up-down-home)
			Down	2 < 1	red	left (home)	left (down-up-home)
	Right	Low	Up	1 < 1	green	right (home)	left (up-home)
			Down	< 1	green	right (home)	left (down-home)
		High	Up	1 < 2	green	right (home)	left (up-down-home)
			Down	2 < 1	green	right (home)	left (down-up-home)
Right	Left	Low	Up	1 > 1	red	left (home)	right (up-home)
			Down	> 1	red	left (home)	right (down-home)
		High	Up	1 > 2	red	left (home)	right (up-down-home)
			Down	2 > 1	red	left (home)	right (down-up-home)
	Right	Low	Up	1 > 1	green	right (home)	right (up-home)
			Down	> 1	green	right (home)	right (down-home)
		High	Up	1 > 2	green	right (home)	right (up-down-home)
			Down	2 > 1	green	right (home)	right (down-up-home)

Note. The same sides for Responses A and B imply response-feature overlap, whereas different sides imply no overlap.

Received October 20, 1997
Revision received July 3, 1998
Accepted October 30, 1998 ■