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ORIGINAL ARTICLE

Attentional control of the creation and retrieval of stimulus–response bindings

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Abstract Two experiments studied the degree to which the creation and retrieval of episodic feature bindings is modulated by attentional control. Experiment 1 showed that the impact of bindings between stimulus and response features varies as a function of the current attentional set: only bindings involving stimulus features that match the current set affect behavior. Experiment 2 varied the time point at which new attentional sets were implemented—either before or after the processing of the to-be-integrated stimuli and responses. The time point did not matter, suggesting that the attentional set has no impact on feature integration proper but controls which features get access to and can thus trigger the retrieval of bindings.

Introduction

The primate cortex is organized in a modular fashion. For example, a visually perceived object like a red ball is not represented by a single code, but by a multitude of feature-related codes in different representational maps, such as a color code in a color map, a shape code in a shape map, a location code in a location map (or even in many location maps, each representing a different reference frame) and so forth (for overviews, see Cowey, 1985; DeYoe & Van Essen, 1988). If people would represent only one object at any given moment, this would not lead to any problem—the object features only need to activate their corresponding codes and the activated ensemble would then correctly represent the feature conjunction that characterizes the object. In everyday life, however, our visual environment is relatively complex and we often see, and seem to be able to perceive, more than one object at a time. This introduces the so-called binding problem (for overviews, see Singer, 1994; Treisman, 1996), the question of how our brain is able to integrate all feature codes that belong to the same object. With respect to the integration of visual features, Kahneman, Treisman, and Gibbs (1992) demonstrated that task-irrelevant stimuli of a complex prime display are particularly effective if they match an upcoming target stimulus in both identity and location, hence there is a specific benefit for feature conjunctions. These authors assumed that the codes of features belonging to the same object are integrated into what they call an *object file*, a temporary cognitive structure containing all the perceptual information about the object and perhaps even more (e.g., semantic information).

Binding problems are not confined to the visual cortex and the integration of visual features, however. Many tasks require the coordination of perceptual input and motor output, which raises the question of how perceptual codes and action-related codes are integrated. To investigate this issue, Hommel (1998) extended the logic of Kahneman et al.'s experimental approach to create conditions under which stimulus features and responses can be repeated or alternated in an orthogonal fashion.[1] As sketched in Fig. 1,

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[1] Research on feature integration in perception (commonly in vision) does not make much contact with feature integration in action planning or across perception and action, and researchers tend to think of the underlying processes as very different. However, not only are the representations of actions no less distributed as the representations of objects (Hommel & Elsner, 2009), thus raising the same kind of binding problems (Stoet & Hommel, 1999), but the functional and computational logic underlying feature integration in creating cognitive representations of objects, action plans, and sensorimotor coordination patterns may well be equivalent (Hommel, 2004).

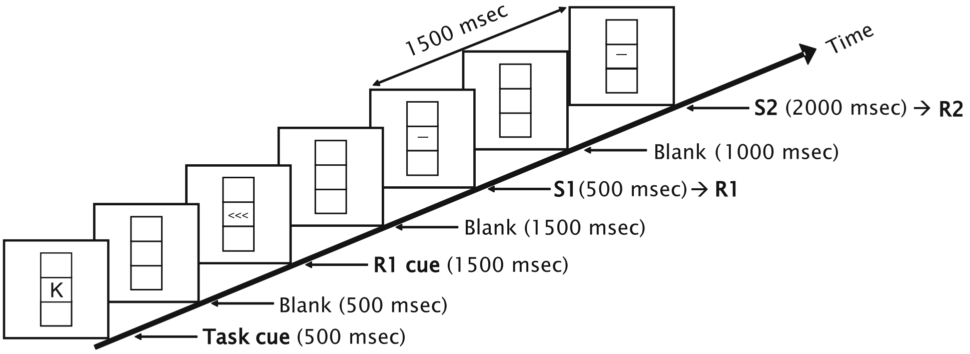

Fig. 1 Sequence of events in Experiment 1. A task cue signaled which task to perform at *S2*. A response cue signaled a left or right key press (*R1*) that was to be delayed until presentation of *S1*, a *red* or *green*, *vertical* or *horizontal bar*. *S2* appeared 1,500 ms later: another *red* or *green*, *vertical* or *horizontal bar*. *S2* signaled *R2*, a speeded left or right key press

he had participants to carry out two responses (R1 and R2) to two different stimuli (S1 and S2) in a row (Hommel, 1998 did not use a task cue, the function of which will be described later). R2 was a binary choice response to a visual feature of S2, such as the vertical vs. horizontal orientation of a bar. In order to measure the impact of stimulus and response repetitions on R2 performance, the features of S1 and R1 varied independently of each other and of S2 and R2. This implied that S1 could not be used to signal the identity of R1 (otherwise S1 and R1 would be no longer independent), so that a precue was used for that purpose. Hence, in each trial the first response (R1) was precued, so that this response could be already prepared (cf., Fig. 1, R1 cue). Then participants saw S1, which served as a mere trigger of R1 and could be of a particular shape and color, and appear in a particular location (not indicated in Fig. 1), and then carried out R1. As R1 was already known, color, shape, and location of S1 were completely irrelevant. A second later, participants carried out a speeded response (R2) to the shape, say, of the second stimulus (S2).

This task has revealed a particular interaction between stimulus repetition (or, more precisely, the repetition of stimulus features) and response repetition—an interaction that suggests that stimulus features and responses are spontaneously integrated. In the study of Hommel (1998) and others, choice performance was found to be better if the relationship between the features of S2 and R2 either completely matched that between S1 and R1 (e.g., VERTICAL-LEFT → VERTICAL-LEFT) or was entirely unrelated (e.g., VERTICAL-LEFT → HORIZONTAL-RIGHT), as compared to conditions with partial matches (e.g., VERTICAL-LEFT → VERTICAL-RIGHT). This partial-repetition cost indicates that the mere pairing of a stimulus and a response (S1 and R1 in this paradigm) leads to the creation of a short-term link between the codes representing them or, as we explain below, between some of these codes. If at least one of these codes is reactivated (i.e., if at least one of the interlinked stimulus and response features is repeated), the whole compound is retrieved in a kind of pattern completion process. This is of little consequence if there is a perfect match and it does not happen with a mismatch (which explains why these two conditions yield comparable results), but it hampers performance if there is a partial match: repeating a stimulus feature would activate an incorrect response and repeating a response feature would activate an incorrect stimulus representation (see Hommel, 2004).

Figure 2 illustrates this mechanism for stimuli that vary in orientation or shape (vertical vs. horizontal) and left and right responses. Let us assume that a horizontal S2 calls for a right key press (R2), as indicated in the right column of the figure, while a vertical S2 requires a left key press. Figure 2a sketches the assumption that S1 features are spontaneously bound to R1. In the example, a right key press was precued and carried out, triggered by S1, which happened to be a horizontal bar. S1 activates the corresponding HORIZONTAL code on the (strongly simplified) shape map and R1 the corresponding code on a spatial response map (thus coding the relevant response feature, see Hommel, 2007). The contiguity-based co-activation of S1 codes and R1 codes is assumed to lead to the creation of an *event file* (Hommel, 1998, 2004), a short-term memory structure linking the stimulus and response codes. Now assume that S2 also consists of a horizontal bar, which according to the instructed mapping requires a right key press (see Fig. 2b). Registering the stimulus leads to the activation of the corresponding HORIZONTAL code. Once this code is activated at least to some degree, it will continuously increase the activation of the associated response code, RIGHT in this case (if we assume a continuous flow from stimulus processing to response selection: e.g., Bogacz, 2007; Eriksen & Schultz, 1979). The two respective codes (HORIZONTAL and RIGHT) were already integrated and connected via the event file from the previous trial (see Fig. 2b), which may or may not facilitate

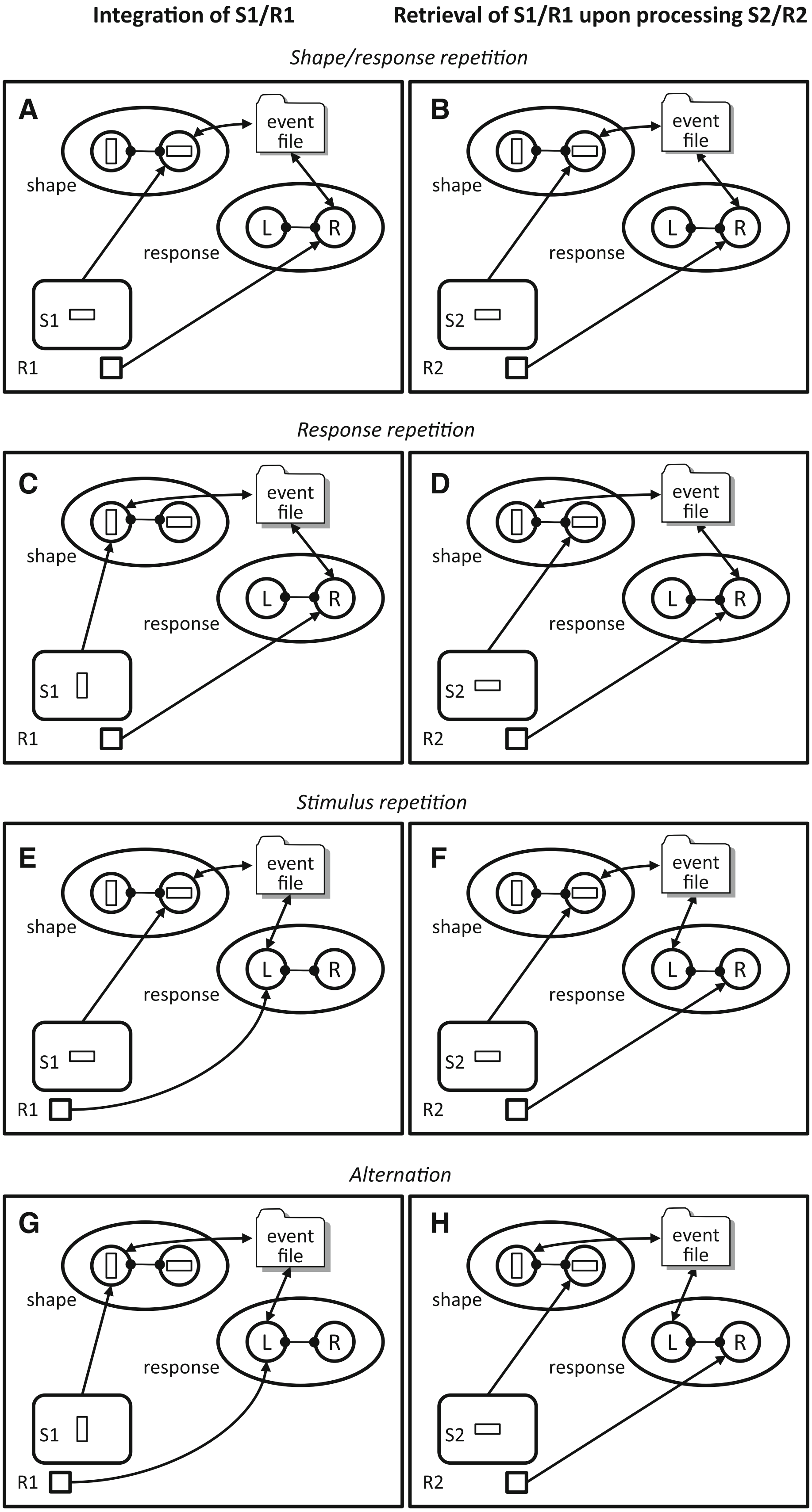

Fig. 2 Explanation of partial-repetition costs from an event-file approach (Hommel, 1998, 2004). In the example chosen, (1) a precued left or right *R1* is carried out, triggered by the mere appearance of a randomly chosen vertical or horizontal bar (*S1*); before (2) a left or right *R2* is signaled by a *vertical* or *horizontal bar* (*S2*). Pairing *S1* and *R1* is assumed to induce the integration of the shape and response feature codes they activate, and the storage of the links between them into an event file (see *left column*). The *panels* **a**, **c**, **e**, and **g** illustrate this process (the stimulus-induced code activation and the creation of associations with the event file) for the combinations of a *horizontal S1* and a *right R1*, a *vertical S1* and a *right R1*, a *horizontal S1* and a *left R1*, a *vertical S1* and a *left R1*, respectively. The *right column* shows four times the same combination of a *horizontal S2* and a *right R2*, combined with the event file created in the situation shown in corresponding panel on the left. The *four rows* represent a complete repetition (**a**, **b**), a response repetition (**c**, **d**), a stimulus repetition (**e**, **f**), and an alternation (**g**, **h**)

the reactivation of the same two codes.[2] In any case, it is clear that this example of a complete repetition trial (repetition of both stimulus features and response) does not create any interfering cross talk or competition.

This is different in the next example, which assumes the repetition of the response and the alternation of the stimulus. As shown in Fig. 2c, R1 will again activate the RIGHT code while the now vertical S1 activates the corresponding VERTICAL shape code. Both codes will be connected via an event file. If R2 is a repetition of R1 but S2 consists of a horizontal bar (as in Fig. 2b), the situation is as sketched in Fig. 2d. Building up activation of the RIGHT code in the process of translating S2 into the proper response will reactivate the previously created event file and spread activation to the VERTICAL code. This creates competition between the two shape codes and delay responding and/or produce a response error (given that the vertical code is mapped onto the left response). Following the same logic, repeating the stimulus and alternating the response (shown in Fig. 2e, f) induce response competition, whereas changing both stimulus and response (shown in Fig. 2g and h) does not even lead to the reactivation of the previous event file and thus produces no harm. It is easy to see that this scenario leads exactly to the outcome obtained—better performance with complete repetitions and alternations (Fig. 2b, h) than with partial repetitions (Fig. 2d, f).

Attentional control

Kahneman et al.'s (1992) approach to feature integration in visual perception suggests that integration is nonselective and considers all features of an object. However, there is evidence that both visual feature integration (Cohen & Shoup, 1997; Maruff, Danckert, Camplin & Currie, 1999; Remington & Folk, 2001) and visuomotor (i.e., stimulus and response) integration (Hommel, 1998, 2007; Hommel & Colzato, 2004) are modulated by intention. For instance, the behavioral effects of bindings between shape and response codes are much stronger than those of color–response bindings if shape is task relevant but color is not (Hommel, 1998; Hommel & Colzato, 2004), whereas the opposite pattern is observed if color is task relevant but shape is not (Hommel, 1998). Likewise, bindings between the relevant shape and irrelevant location of a stimulus affect behavior if the response alternatives are defined by location (i.e., if left versus right responses are used) but not if the response alternatives are defined by the number of key presses, a non-spatial feature that is (Hommel, 2007). Hence, the likelihood or impact of binding seems to be determined by task relevance or, more precisely, by whether the given feature varies on a dimension that is explicitly or implicitly defined as relevant in the task (be it for discriminating between stimulus or response alternatives).

Other manipulations of attention had much less impact, however. Even though the task introduced by Hommel (1998) does not require any discrimination or identification of S1, or any consideration of the relationship or mapping between S1 and R1, people seem to bind at least some of the features of S1 and R1. Even making the visual S1 entirely task irrelevant by having R1 carried out in response to an additional visual or auditory signal does not modify the size of S1–S1 (e.g., shape–location) and S1–R1 (e.g., shape–response) binding effects (Hommel, 2005). This suggests that attentional control settings (induced by task relevance) may not determine whether feature bindings or event files are created or retrieved. Rather, they only seem to specify the dimensions on which features are considered. The present study sought to investigate in more detail how this works, that is, how attentional control mediates the processing of event files and which processes are modulated in which ways.

One possible scenario of how attentional control may impact the processing of event files relates to the process of integration, that is, to the binding of stimulus and response information (on which we will focus in the following) upon S1 presentation and R1 performance. As Hommel (2004) suggested, implementing an attentional set (e.g., by mapping R2 locations to the shapes of S2 and thus making shape and location information task relevant) may be prime-related, task-relevant feature dimensions, so that the feature codes belonging to these dimensions will be more strongly activated by stimuli possessing the corresponding features. This possibility is sketched in Fig. 3a. In the example, it is assumed that stimuli vary in shape (horizontal vs. vertical bars) and color, and are responded to by left and right responses. The shape of S2 is as task relevant as the location of responses, which is assumed to prime the shape and the spatial response maps. Stimulus features

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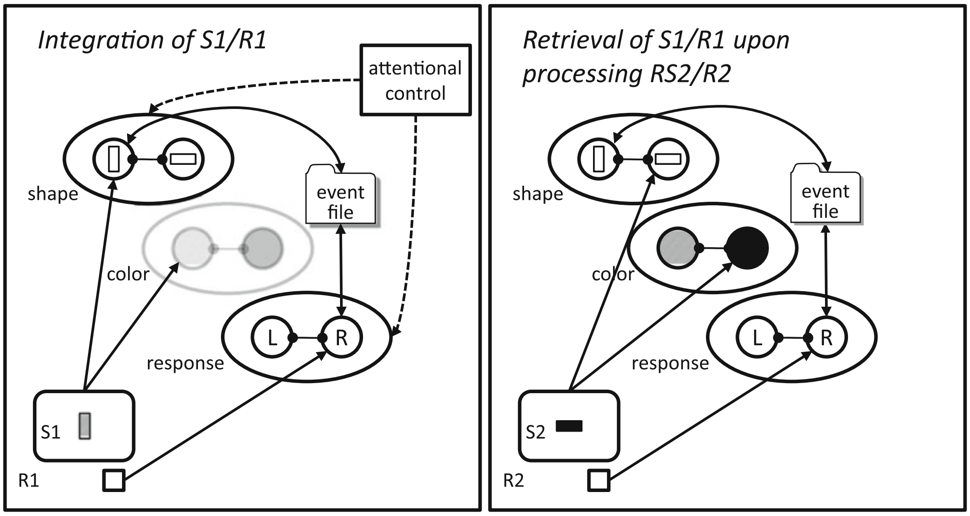
[2] Among other things, the relative benefit of complete repetitions depends on the question whether selecting a response presupposes the mere activation of the relevant feature codes (as for example considered by Jolicœur, Tombu, Oriet & Stevanovski, 2002) or the completed integration of these codes (as suggested by Kahneman et al., 1992). Specific predictions, especially regarding the comparison with alternations, are further complicated by the observation that complete stimulus repetitions seem to induce a tendency to shortcut response selection (Bertelson, 1963; we will come back to this issue in the discussion of Experiment 2) and that alternations may benefit from "integrated competition" (Duncan, 1996), in the sense that a previously created binding between competing features may make it easier to reject them as "one unit". Given these complications, we neglect the precise relationship between complete repetitions and alternations (which empirically often produce comparable results) but focus on the observation that, and the explanation, why partial repetitions produce worse performance than both complete repetitions and alternations.

A Attentional control of integration



B Attentional control of retrieval

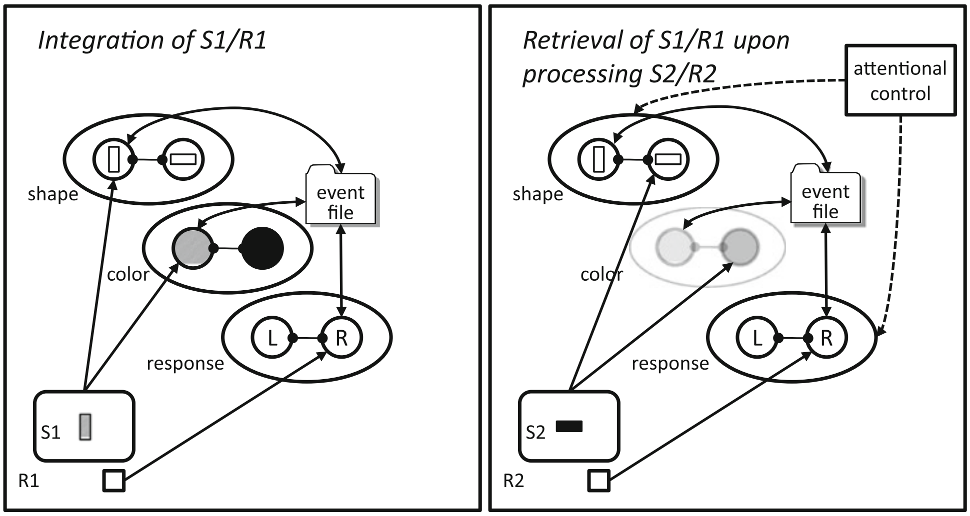


Fig. 3 Two possible scenarios of how attentional control settings may affect event-file processing. **a** Attention may control the integration of stimuli and responses, i.e., *S1* and *R1* in our example. *S1* varies in shape and color, and *R2* in location. Activated feature codes are automatically integrated into an event file, as shown in the *left panel*. However, attentional control regulates the amount of activation feature codes can reach by priming task-relevant coding dimensions, a process that can be considered multiplying code activation. The assumption is that because of this only feature codes on primed dimensions pass the integration threshold and become part of the event file. In the example, this is true for shape and response codes but not for color codes, which are symbolized by the faded color map and a missing link of the activated color code to the event file. Later, upon processing *S2* and increasing the activation of *R2*, the corresponding codes are again activated (see *right panel*, which shows the example of a stimulus with a different shape and color as *S1* mapped onto the right response). As the response is repeated, activating the RIGHT response code will reactivate the previous event file and spread activation to the "wrong" and therefore competing shape code. Irrespective of the current attentional set (which may well exist but is not shown because it would be theoretically irrelevant), the color code that was activated by *S1* will not be reactivated because it was not linked to the event file. **b** Alternatively, attention may not affect the integration of *S1* and *R1* codes, which is why all feature codes become part of the event file and the attentional control settings is not considered (see *left panel*), but may control the retrieval of codes that get access to, and can thus retrieve an event file (see *right panel*). In this case, the task-irrelevant color code would be a part of the event file representing the *S1–R1* episode, but only the *S2*/*R2* codes that fall on task-relevant and therefore primed dimensions and reactivate a previous event file. The fading of the color map thus refers here to the retrieval potential of codes but not to the likelihood of code integration (i.e., *S2* color would still be integrated)

coded on a primed map are assumed to reach higher activation levels. If we further assume that feature codes are integrated only if their activation passes a hypothetical integration threshold, it follows that making a feature dimension task relevant increases the likelihood that features coded on this dimension are more likely to be integrated and thus contained in the respective event file. In the example, this would imply that shape–response bindings are more likely to be created than color–response bindings—a relationship that would be turned around by making color task relevant. This is precisely what the data show (Hommel, 1998).

There is another possibility, however. Features may be integrated in a more or less automatic and nonselective fashion, which would explain why binding-related effects are not very sensitive to distracting attention or otherwise reducing the available attentional capacity (Hommel, 2005, 2007; Hommel & Colzato, 2004). Instead, what is selective and depending on the attentional set may be the *retrieval* of just-formed bindings. As pointed out by Logan, Taylor, and Etherton (1996) and Memelink and Hommel (2013), reviewing aspects of an event may not retrieve all event representations that have been previously formed, so that retrieval-based effects would underestimate the amount of actually encoded information. Implementing an attentional set may thus make some features better retrieval cues than others and thereby effectively restrict retrieval to task-relevant dimensions. This possible scenario is shown in Fig. 3b. The idea is that feature integration is independent of the attentional setting, so that the codes of all stimulus and response features are integrated and bound into an event file alike. However, what the current attentional control settings may do instead is to increase the weight of features on task-relevant stimulus and response feature maps in the retrieval process (Memelink & Hommel, 2013). That is, features on task-relevant dimensions (in this example: shape, as it defines S2, and location, as it defines R2) have a stronger potency to reactivate previously built event files. If so, shape and location will be very effective retrieval cues for reactivating the just-created feature binding, while it should matter less whether color (which in the example has no relevance whatsoever) is repeated or not. Accordingly, finding that color–response bindings have no effect in a shape task, say, may thus not mean that such bindings were not created but, rather, that they were not retrieved.

Aim of study

The aim of the present study was twofold. For one, we wanted to investigate in more detail how flexible and dynamic the attentional control of the creation and/or retrieval of feature bindings is. The available evidence suggests that task relevance has some impact but hitherto the manipulation of relevance was rather coarse (i.e., a given feature was relevant or irrelevant for a whole experiment) and took place between participants, so that the conclusions rest on comparing different experiments in some cases with different designs. More direct evidence for attentional control would be provided by showing that which features are bound, or which bindings affect behavior, can vary from trial to trial as a function of the currently implemented attentional set. Our aim was thus not just to demonstrate that new *feature values* can be bound and retrieved in each trial (as the available evidence already suggests) but to test whether the way this binding and/or retrieval is modulated by task goals (i.e., the “intentional weighting” of feature dimensions; see Memelink & Hommel, 2013) can flexibly vary from trial to trial.

We attempted to show this in Experiment 1 by adopting the task of Hommel (1998) which, as described already, consists of a priming event (S1, the response trigger, and R1, a prepared response) and a probe event (S2, a particular shape–color conjunction, and R2, a binary-choice response to the shape or color of S2). However, instead of making shape or color (of S2 and thus for R2) relevant for a whole session, we precued one dimension in advance of a given prime–probe sequence. We assumed that precuing a dimension would lead to the implementation of a corresponding attentional set favoring (i.e., weighting more strongly) stimulus information defined on the shape or color dimension, respectively (cf., Folk, Remington, & Johnston, 1992; Memelink & Hommel, 2013; Pratt & Hommel, 2003). This may affect the creation or the retrieval of feature bindings, or both. In either case, binding-related effects (i.e., the *partial-repetition costs* of partial S–R repetitions as compared to complete repetitions or alternations) should be more pronounced for stimulus features matching the currently precued dimension. Notably, effects of shape–response binding should be stronger after a shape precue than after a color precue, while the opposite should be true for color–response binding.

The second aim of our study was to disentangle attentional effects on the creation and the retrieval of feature bindings and to see whether the scenario sketched in Fig. 3a or in b would be more realistic. The design of Experiment 1 did not allow for distinguishing one kind of effect from the other because creation and retrieval occurred (presumably[3]) under the same attentional set. To achieve this, we ran Experiment 2, in which we varied the time point at which the dimensional cue was presented: either before or after S1 presentation. We reasoned that late cues would only affect the attentional set under which S1/

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[3] This reasoning assumes that attentional sets are implemented immediately after cue processing, so that the presentation of both S1 and S2 falls under the same set. One may object that, given that the set was unnecessary for processing S1, it may not have been implemented before S1 processing was completed, so that processing S2 but not S1 took place under the respective set. This consideration can be tested by comparing trials in which the set was the same as in the trial before (set repetition trials) with trials in which the sets differed (set alternation trials). Experiment 1 will show that set repetitions and alternations produced pretty much the same result pattern, which renders the objection unfounded.

R1 features are retrieved, while early cues would affect both the integration and the retrieval of these features. Accordingly, finding that only early cues would modulate event-file effects would point to an impact of the attentional set on the binding of features, while finding an effect of late cues would point to an impact on retrieval.

Experiment 1

As pointed out, previous research suggests that the impact of feature integration on behavior varies as a function of the task relevance of the stimulus or response dimensions involved. In particular, conjunctions between features that fall on a directly or indirectly task-relevant dimension have been observed to produce larger and more reliable effects than features from task-irrelevant dimensions (Hommel, 1998, 2007). However, previous manipulations of task relevance were done between experiments and participants, so that task relevance was constant in a given session and for a given participant. In the present Experiment 1, we intended to provide more direct support for the assumption that the task-relevance effects reflect attentional biases induced by corresponding attentional sets (Folk et al., 1992; Pratt & Hommel, 2003). Accordingly, the relevant stimulus dimension (i.e., the dimension of S2 to which R2 was carried out) was cued from trial to trial, as shown in Fig. 1. In each trial, participants first saw a (task) cue indicating the relevant S2 dimension (color or shape) before running through the same sequence of events as in the study of Hommel (1998): They were cued to prepare a left- or right-hand key press (R1), which they carried out as soon as S1—the *prime stimulus*—was presented. Even though the identity of S1 did not matter for the response, it varied in color (red vs. green) and shape (horizontal vs. vertical line). One second later S2 appeared to signal R2, which was a speeded choice reaction to either the color or the shape of S2, depending on the task cue. The crucial question was whether the interactions between color and response and between shape and response would vary with the relevant dimension of the current task, that is, whether the size of partial-repetition costs (repeating the stimulus feature but not the response, or vice versa, as compared to complete S–R repetitions or alternations) would increase if the stimulus feature matches the current attentional set.

Methods

Participants

Twenty students of the Leiden University took part for pay. All reported having normal or corrected-to-normal vision, and were not familiar with the purpose of the experiment.

Apparatus and stimuli

The experiment was controlled by a Targa Pentium III computer, attached to a Targa TM 1769-A 17″ monitor. Participants faced three gray square outlines, vertically arranged, as illustrated in Fig. 1, but all stimuli were presented in the middle frame (the top and bottom frames were kept to allow optimal comparison with other experiments in which stimulus location was varied). From a viewing distance of about 60 cm, each of these frames measured 2.6° × 3.1°. A thin vertical line (0.1° × 0.6°) and a some what thicker horizontal line (0.3° × 0.1°) served as S1 and S2 alternatives, which were presented in red or green. The Task Cue (TC) consisted of the letters "*K*" or "*V*" (the first letter for the words color and shape in Dutch) to signal which feature dimension of S2 was relevant for selecting R2. The Response Cue (RC) consisted of a left- or right-pointing arrow, indicating R1 (a left and right key press, respectively). Responses to S1 and S2 were made by pressing the left or right shift key of the computer keyboard with the corresponding index finger.

Procedure and design

In two 40-min sessions, participants carried out two responses per trial. R1 was a simple reaction with the left or right key, as indicated by the response cue. It had to be carried out as soon as S1 appeared, independent of its color or shape. Participants were informed that there would be no systematic relationship between S1 and R1, or between S1 and S2, and they were encouraged to respond to the onset of S1 only, disregarding the stimulus' attributes. R2 was a binary-choice reaction to the color or shape of S1, depending on the task cue ("*K*" indicating responses to the color of S2 and "*S*" indicating responses to the shape or orientation). The different mappings of left and right key presses to the two stimulus colors and the two stimulus shapes were balanced across subjects.

The sequence of events in each trial is shown in Fig. 1. TC appeared for 500 ms to signal a R2 to the color or shape of S2. After a 500-ms blank, a 1,500-ms RC signaled a left or right key press (R1) that was to be delayed until presentation of S1. After another 1,500-ms blank interval, S1 appeared for 500 ms, it was a red or green vertical or horizontal line. R1 was to be carried out irrespective of the particular features of S1. After a further 1,000-ms blank interval, S2 appeared to signal R2, a speeded left or right key press. S2 appeared for 2,000 ms or until R2 was executed. If a response was incorrect auditory feedback was presented. R2 speed and accuracy were analyzed as a function of the repetition vs. alternation of stimulus color and shape, of the response and of the repetition or alternation of the attentional set (i.e., the task). The experiment comprised 512 trials, composed by a factorial combination of the two colors (red vs. green) and shapes (vertical vs. horizontal line) of S2, the two attentional sets, the relation between the present and the previous attentional set (repetition versus alternation), the repetition vs. alternation of stimulus color, the repetition vs. alternation of stimulus shape, and the repetition vs. alternation of the response ($2 \times 2 \times 2 \times 2 \times 2 \times 2 \times 2 = 128$). Each of these 128 combinations was repeated 4 times, amounting to 512 trials in total.

Results

Mean reaction times (RTs) and error rates were computed as a function of attentional set or task, repetition versus alternation of the attentional set or task (see footnote 3), repetition versus alternation of stimulus color and shape, and repetition versus alternation of the response (see Table 1 for means). ANOVAs were performed using a five-way design for repeated measures (see Table 2 for results). The significance criterion for all analyses was set to $p < .05$.

The RT analysis revealed six significant effects. Two of them were of minor theoretical interest: First, a main effect of color repetition indicated that repeating color yielded faster responses than alternations (443 vs. 453 ms). Second, an interaction between response repetition and task (i.e., attentional-set) repetition showed that repeating a response sped up RTs if the task was repeated (442 vs. 449 ms) but tended to slow down RTs if the task alternated (453 vs. 449 ms). This observation amounts to a conceptual replication of a similar finding reported by Rogers and Monsell (1995), even though in the present study the two respective S–R events (S2 and R2 of the previous trial and S2 and R2 of the present trial) were separated by another event (S1 and R1 of the present trial) that did not belong to the task to which the repeated or changing attentional set referred.

The remaining four effects were of greater interest for our purposes. As shown in Fig. 4, the standard interactions between color and response and between shape and response were obtained, with better performance if the stimulus feature and the response were both repeated or both alternated. In other words, there were partial-overlap costs indicating that repeating a stimulus feature but not the response, or vice versa, impairs performance. Even more interestingly, both interactions were modified by task, that is, attentional set. As the figure shows, the color–response interaction was more pronounced under a color set than under a shape set, whereas the shape–response interaction was more pronounced under a shape set than under a color set.

The error rates revealed a similar picture. As Fig. 4 indicates, color–response and shape–response interactions followed the same pattern as the RTs, and the former was also more pronounced in the color than the shape task. Numerically, the shape–response interaction was also more pronounced in the shape than in the color task, but the three-way interaction was far from significance. In addition, error rates were lower if the task is repeated than alternated (5.8 vs. 7.2 %) and the better performance with color repetition than alternation that was obtained for task repetitions (6.6 vs. 7.3 %) disappeared with task alternations (7.4 vs. 7.0 %).

Discussion

As expected, the sizes of partial-repetition costs increased if the respective stimulus feature matched the current attentional set. This replicates previous observations (e.g., Hommel, 1998; Hommel & Colzato, 2004) in a within-

Table 1 Experiment 1: Means of mean reaction times for responses to stimulus 2 ($\mathrm{RT}_{\mathrm{R2}}$; in Ms) and percentages of errors on R2 ($\mathrm{PE}_{\mathrm{R2}}$), as a function of task (color vs. shape), task repetition vs. alternation, the match between response 1 and response 2, and the feature match between stimulus 1 and stimulus 2

	Task															
	Color task				Shape task				Color task				Shape task			
	Response															
	Repeated		Alternated		Repeated		Alternated		Repeated		Alternated		Repeated		Alternated	
	$\mathrm{RT}_{\mathrm{R2}}$	$\mathrm{PE}_{\mathrm{R2}}$	$\mathrm{RT}_{\mathrm{R2}}$	$\mathrm{PE}_{\mathrm{R2}}$	$\mathrm{RT}_{\mathrm{R2}}$	$\mathrm{PE}_{\mathrm{R2}}$	$\mathrm{RT}_{\mathrm{R2}}$	$\mathrm{PE}_{\mathrm{R2}}$	$\mathrm{RT}_{\mathrm{R2}}$	$\mathrm{PE}_{\mathrm{R2}}$	$\mathrm{RT}_{\mathrm{R2}}$	$\mathrm{PE}_{\mathrm{R2}}$	$\mathrm{RT}_{\mathrm{R2}}$	$\mathrm{PE}_{\mathrm{R2}}$	$\mathrm{RT}_{\mathrm{R2}}$	$\mathrm{PE}_{\mathrm{R2}}$
	Task repetition								Task alternation							
Neither	456	9.37	421	2.81	466	7.81	445	2.81	478	11.87	453	6.56	473	6.25	422	4.06
C(olor)	433	5.00	453	6.87	455	7.50	455	5.94	435	6.56	454	10.31	449	5.94	445	7.50
S(hape)	458	7.19	432	5.00	441	3.12	475	5.31	466	9.06	435	6.87	456	5.00	475	6.56
SC	399	1.56	442	9.69	430	3.44	466	8.75	422	2.81	453	10.31	443	5.62	454	10.31

Table 2 Results of analysis of variance on mean reaction time of correct responses (RT) and percentage of errors (PE) for Experiment 1

Effect	*df*	RT_{R2}		PE_{R2}	
		MSE	*F*	MSE	*F*
Alternation (Alt)	1,19	2,222.56	1.95	42.26	8.12**
Task	1,19	8,188.05	1.90	104.91	1.51
Color (Col)	1,19	2,586.40	6.36*	38.45	0.99
Shape (Shp)	1,19	2,734.54	0.46	27.04	1.16
Response (Rsp)	1,19	2,427.21	0.11	36.40	2.29
Alt × Task	1,19	2,824.13	3.12	35.50	1.87
Alt × Col	1,19	1,726.07	0.55	36.78	0.08
Task × Col	1,19	1,757.50	0.94	40.13	6.04*
Alt × Task × Col	1,19	4,393.28	0.02	32.54	0.32
Alt × Shp	1,19	997.37	0.70	48.17	0.03
Task × Shp	1,19	2,996.22	2.44	41.41	0.78
Alt × Task × Shp	1,19	1,883.02	1.01	46.70	2.19
Col × Shp	1,19	1,683.57	3.36	24.09	0.00
Alt × Col × Shp	1,19	1,513.16	1.41	32.557	0.00
Task × Col × Shp	1,19	1,122.19	0.07	41.28	0.25
Alt × Task × Col × Shp	1,19	1,239.30	3.84	40.51	0.01
Alt × Rsp	1,19	941.72	4.72*	37.30	0.86
Task × Rsp	1,19	2,045.51	0.28	25.55	0.06
Alt × Task × Rsp	1,19	2,348.68	1.05	19.05	0.16
Col × Rsp	1,19	2,340.24	22.90**	31.26	51.88**
Alt × Col × Rsp	1,19	1,522.64	0.00	34.62	0.00
Task × Col × Rsp	1,19	3,307.36	5.29*	42.31	8.55**
Alt × Task × Col × Rsp	1,19	1,844.77	0.42	27.17	0.00
Shp × Rsp	1,19	1791.08	15.88**	46.42	19.89**
Alt × Shp × Rsp	1,19	2,326.95	0.28	32.75	2.28
Task × Shp × Rsp	1,19	818.65	14.56**	31.67	0.23
Alt × Task × Shp × Rsp	1,19	2,911.10	0.08	24.22	0.30
Col × Shp × Rsp	1,19	2,017.68	0.57	24.27	0.06
Alt × Col × Shp × Rsp	1,19	1,579.22	0.39	20.41	0.07
Task × Col × Shp × Rsp	1,19	2,326.63	2.98	45.29	0.16
Alt × Task × Col × Shp × Rsp	1,19	1,505.76	0.77	48.48	0.01

* $p < .05$, ** $p < .01$

participants design and with a trial-to-trial manipulation of attentional set. In view of this finding, it makes sense to assume that the reliance of feature bindings on task relevance reflects not so much general expectations, biases, or strategies developed during an experimental session but, rather, the workings of the attentional priming of task-relevant perceptual dimensions (Folk et al., 1992; Pratt & Hommel, 2003).

It is interesting to note that there was no any indication that this interaction between attentional set and feature integration might depend on the repetition or alternation of the task and, hence, the attentional set. This has an important implication with respect to the possible objection that our participants may not have implemented the attentional set upon processing of the task cue but only after S1 has been processed (see footnote 3). If this would have been the case, task repetitions would mean that S1 and S2 were processed under the same attentional set, while task alternations would imply that S1 and S2 were processed under different attentional sets. The fact that our results are comparable for task repetitions and task alternations does not prove the objection wrong, but it does render it irrelevant—either because people did implement the new attentional set upon cue processing and/or because the attentional set does not affect S1(-R1) processing but S2(-R2) processing. The latter possibility will be tested (and confirmed) in Experiment 2.

Though not of central importance for present purposes, it is worth mentioning that the interaction of color and shape repetition approached significance, $p < .08$, indicating that repeating color but not shape, or vice versa, tended to impair performance. Previous studies have

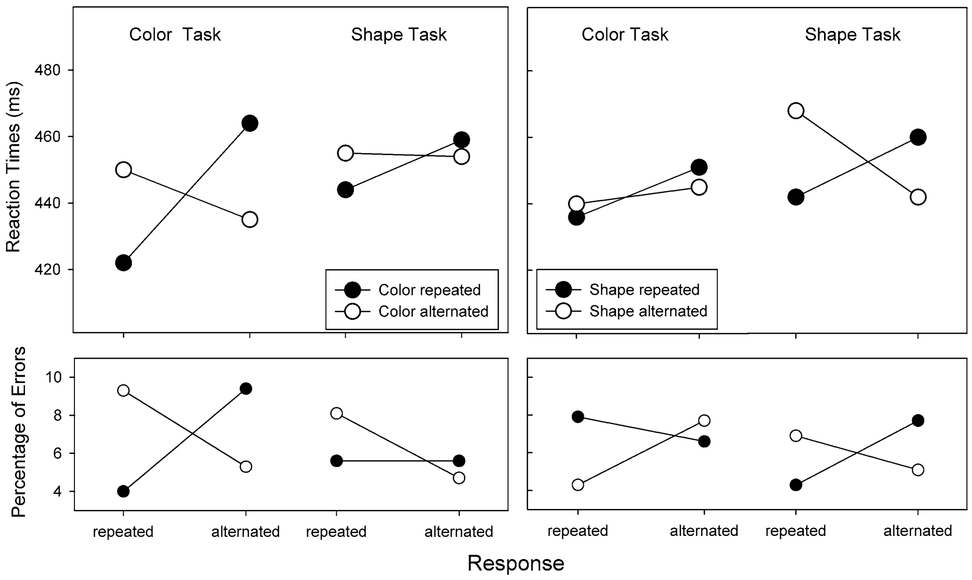

Fig. 4 Reaction times and percentage of errors in Experiment 1, as a function of response repetition, color repetition, and task (*left panels*) and response repetition, shape repetition, and task (*right panels*)

sometimes found reliable interactions (e.g., in some experiments of Hommel, 1998), and we will encounter such interactions in some of the analyses in Experiment 2. The fact that these interactions are not always obtained points to the possibility that either the creation of stimulus–stimulus bindings (i.e., object files in the sense of Kahneman et al., 1992) or at least their impact on behavior is under the control of task and/or intentional factors. Consistent with that, Colzato, Raffone, and Hommel (2006) observed that color–shape interactions disappear with practice if only one stimulus dimension is task relevant. If we assume that this finding reflects the practice-induced sharpening of the attentional set, the observation of reliable interactions would be attributable to the not-yet completed tailoring of the attentional set to the task at hand.

Experiment 2

Experiment 1 confirms previous observations that task relevance modulates the impact of feature bindings on behavior and it shows that this modulation derives from the currently implemented attentional set. The question that Experiment 2 was supposed to answer was exactly which process is being modulated. The design of Experiment 1 does not allow us to disentangle attentional effects on feature integration from effects on the retrieval of bindings (cf., Fig. 3), because implementing an attentional set in response to the task cue would always affect both the binding of features during S1–R1 processing and the retrieval of the thereby created bindings upon S2–R2 processing. In Experiment 2, we therefore introduced a second, later point in time at which the task cue could appear, namely, right after the processing of S1 and R1 was completed. This made sure that S1–R1 processing and S2–R2 processing took place under different attentional sets—at least in trials where the current set was different from the previous one. Accordingly, we were able to disentangle effects on integration and on retrieval: If the impact of stimulus–response (and perhaps other) bindings would be still modulated by a late task cue (i.e., after R1), this would point to a retrieval effect, whereas the observation that task modulations are restricted to early cues would point to an integration effect.

On the one hand, the aim of our study required the use of external task cues. A blocked design or task cues informing about multiple trials were no option because they would not have allowed us to manipulate participants' attentional sets on a trial-to-trial basis. On the other hand, however, presenting an external cue in between R1 and S2 raises the question whether and to which degree event-file effects are sensitive to intervening events. The original effect refers to two events that occur in direct succession and one may wonder whether they are affected by presenting a new perceptual event in between. Indeed, given that all combinations of features are commonly balanced across event-file experiments, the fact that the relation between features at trial n and features at trial $n - 1$ matters at all shows that recency must play a role. For instance, it may be that intervening effects are overwriting the previous event file, which would imply that a late cue might interfere with the consolidation and/or the maintenance of S1–R1 bindings. Fortunately, there is considerable evidence that one single event is insufficient to eliminate event-file effects. Hommel (2005) found that presenting a visual S1 close in time to an auditory distractor did not prevent successful integration and retrieval of S1/R1 features. Likewise, Colzato, van Wouwe, and Hommel (2007) observed robust event-file

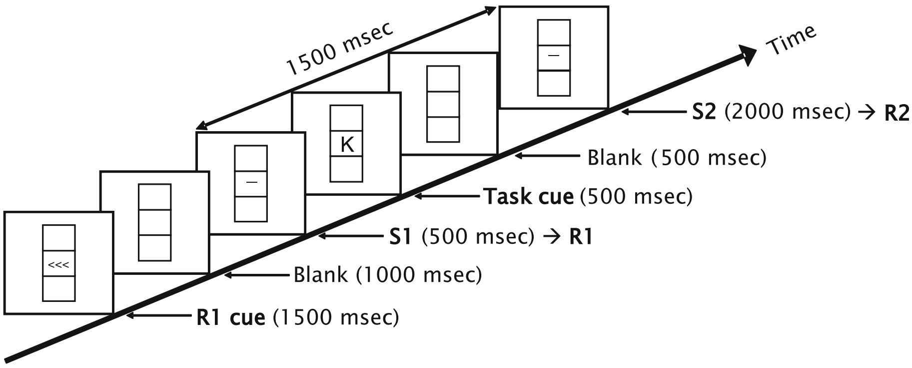

Fig. 5 Sequence of events in late-cue trials of Experiment 2 (early cue trials were as shown in Fig. 1)

effects in a task where participants were presented with positive or negative pictures in between S1/R1 and S2/R2.

Another possibility is that the change of an attentional set in response to a task cue is so resource-demanding that it affects the consolidation of feature bindings. If so, it might be that late cues interfere with the consolidation and/or the maintenance of S1/R1 feature bindings. While this might work against the observation of event-file effects, Pösse, Waszak, and Hommel (2006) reported reliable effects even when S1/R1 and S2/R2 were separated by two trials (including stimuli and responses) of another task. Hence, even if late cues might be expected to reduce the size of event-file effects, they were unlikely to prevent such effects from occurring (we will evaluate this issue in the "Conclusions"). In any case, to make sure that possible outcomes would not depend on the choice of a particular kind of task cue, we decided to run two versions of the same experiment: one with visual cues, just as in Experiment 1, and one with auditory cues. We reasoned that one possible advantage of the auditory cue might be that it interferes less with the processing of the visual S1 information, which might produce somewhat larger effects. However, it might also be that switching attention back and forth between visual and auditory information produces interference (Cohen & Rist, 1992), which would have the opposite effect.

Methods

Thirty-six new students of the Leiden University took part for pay, 20 in the visual-cue condition and 16 in the auditory-cue condition. All reported having normal or corrected-to-normal vision and were not familiar with the purpose of the experiment. The experiment consisted of four 40-min sessions. The procedure was as in Experiment 1, with the following exception. In the visual-cue group, the TC consisted of the letters "*K*" or "*V*" to signal the color and the shape task, respectively, just like in Experiment 1. In the auditory-cue group, however, the TC consisted of the auditorily presented words "kleur" and "vorm" (Dutch for "color" and "shape"), spoken by a male human voice, of about 500 ms duration. In some 32-trial blocks, the TC was presented at the beginning of the trial, as in Experiment 1 (the early cue condition). In other, alternating 32-trial blocks the TC appeared 500 ms after S1 (the late cue condition, see Fig. 5).[4] This required that the first response had to be given within 500 ms. Upon failure to respond within 500 ms, the trial started anew. Due to the additional manipulation of TC time point, the number of trials increased to 1,024.

Results and discussion

Before analyzing the impact of the time point at which the task cue was presented, we checked whether the early-cue condition replicated our main findings from Experiment 1. Indeed, an ANOVA on the RT data from Experiment 1 and the early-cue condition from Experiment 2 with experiment as between-participants factor yielded reliable interactions between color and response repetition, $F(1,54) = 41.02$, $p < .001$, and between shape and response repetition, $F(1,54) = 52.22$, $p < .001$. Again, both interactions were further modified by task (i.e., attentional set), $F(1,54) = 13.92$, $p < .001$, and $F(1,54) = 6.93$, $p < .05$, but none of these three-way interactions were modified by the experiment, $Fs < 1$. Thus, Experiment 2 replicated all relevant aspects of Experiment 1.

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[4] One might argue that a task cue that appears 500 ms after S1 onset may still affect S1–R1 integration, which may blur the distinction between early and late cues. Even though it is impossible to rule that out entirely, it is rather unlikely. First, processing and interpreting the task cue must have taken some time, we would guess more than 200 ms. Second, processing the auditory cue must have taken even longer, which is evident from the increase in mean RT, and yet this did not interact with binding effects. Third, task switching studies have shown that shifting attention from one dimension to another is a rather capacity demanding and slow process, often taking several hundred milliseconds (e.g., Meiran, 1996; Rogers & Monsell, 1995). Considering all these complications, we doubt that the attentional control settings that were signaled by late cues were up and running much earlier than at S2 presentation—a time point at which stimulus–response bindings already start to decay (Hommel & Colzato, 2004).

Table 3 Experiment 2: Means of mean reaction times for responses to stimulus 2 (RT_{R2}; in Ms) and percentages of errors on R2 (PE_{R2}), as a function of cue type (visual vs. auditory), cue (early vs. late), task (color vs. shape), switch, the match between response 1 and response 2, and the feature match between stimulus 1 and stimulus 2

Response	Early cue								Late cue							
	Color task				Shape task				Color task				Shape task			
	Repeated		Alternated		Repeated		Alternated		Repeated		Alternated		Repeated		Alternated	
	RT_{R2}	PE_{R2}	RT_{R2}	PE_{R2}	RT_{R2}	PE_{R2}	RT_{R2}	PE_{R2}	RT_{R2}	PE_{R2}	RT_{R2}	PE_{R2}	RT_{R2}	PE_{R2}	RT_{R2}	PE_{R2}
Visual cue																
Task alternation																
Neither	477	14.69	480	4.38	495	10.63	462	6.88	491	11.56	454	7.50	493	6.88	494	2.81
S(hape)	485	6.88	472	5.94	465	7.50	510	8.75	490	8.13	468	5.63	477	6.25	474	6.88
C(olor)	462	6.56	494	8.44	474	6.25	473	9.06	459	7.19	497	9.06	482	5.94	492	4.06
SC	442	5.00	487	13.13	469	3.75	494	10.31	448	5.31	470	9.06	485	4.38	504	8.13
Task repetition																
Neither	468	10.94	469	4.06	476	7.81	485	2.81	472	8.75	459	3.13	472	4.69	467	3.44
S(hape)	472	6.56	467	6.88	463	5.00	505	6.25	478	10.63	452	3.13	469	3.75	479	6.25
C(olor)	480	7.19	481	6.56	472	5.94	478	7.19	460	6.25	472	7.19	484	6.25	470	5.63
SC	437	4.69	504	11.56	455	1.88	484	7.81	449	4.38	464	5.63	459	4.38	471	8.75
Auditory cue																
Task alternation																
Neither	556	14.79	490	10.17	530	15.88	523	9.13	547	11.50	501	12.14	538	12.27	520	8.49
S(hape)	542	7.82	552	13.51	514	7.94	524	15.47	512	11.92	516	4.95	505	7.63	492	12.42
C(olor)	513	11.99	503	10.48	546	11.12	506	10.69	494	13.02	524	13.71	546	12.24	512	10.23
SC	488	9.46	523	14.23	499	8.84	552	15.91	515	5.99	508	14.23	495	6.33	525	15.50
Task repetition																
Neither	554	19.42	541	10.50	577	14.60	553	7.68	541	16.12	547	8.54	566	11.81	521	9.86
S(hape)	526	15.91	527	13.02	560	18.73	568	14.66	543	13.74	510	9.99	554	13.12	584	13.08
C(olor)	525	19.54	526	16.38	542	14.89	524	14.08	515	10.85	530	12.85	578	10.90	542	11.34
SC	486	11.75	578	20.18	504	7.84	603	18.88	501	13.16	499	15.80	561	6.12	594	17.33

The next analyses included data from early- and late-cue conditions but were restricted to task alternations (see Table 3). The latter measure was taken to make sure that S1 and S2 were always processed under the same attentional set if the task cue was presented early (i.e., under the new attentional set signaled by the task cue) and under different attentional sets if the task cue was presented late (so that S1/R1 would be processed under the previous set and S2/R2 under the new set signaled by the task cue). RTs and error rates underwent six-way ANOVAs with the between-participants factors such as color repetition, shape repetition, response repetition, task (shape versus color task), and time point of cue presentation (early versus late), and the between-participant factor cue modality (visual versus auditory).

Reaction times

The results of the RT analysis fall into four clusters (see Table 4). The first consists of three theoretically less interesting and in part unsurprising effects. Participants were faster in the color task than in the shape task (498 vs. 516 ms) and faster if color was repeated than if it was alternated (504 vs. 510 ms). A cue-modality main effect showed that responses were faster with visual than with auditory cues (471 vs. 543 ms) suggesting that, as suspected, switching back and forth between two modalities worked against optimal preparation for the visual stimuli (Cohen & Rist, 1992).

The second cluster relates to the time point of cue presentation and shows that the late presentation of the cue (i.e., in between S1/R1 and S2/R2) reduced or eliminated a number of repetition effects—confirming our suspicion that presenting an event after S1 and R1 might affect the consolidation and/or maintenance of their episodic traces. Time point interacted with response repetition, indicating that response repetitions were faster than alternations with early cues (500 vs. 518 ms) but not with late cues (506 vs. 504 ms). Time point also mediated the interactions between shape and response and between color and response (to be discussed below), due to these interactions being pronounced

Table 4 Results of analysis of variance on mean reaction time of correct responses ($\mathrm{RT}_{\mathrm{R2}}$) and percentage of errors ($\mathrm{PE}_{\mathrm{R2}}$) for Experiment 2 for alternating-task trials

Effect	$\mathrm{RT}_{\mathrm{R2}}$		$\mathrm{PE}_{\mathrm{R2}}$	
	MSE	*F*	MSE	*F*
Modality (Mod)	1474271.53	5.41*	15648.93	11.09**
Cue	4575.40	0.46	821.23	12.19***
Cue × Mod	3173.44	0.38	293.37	4.35*
Task	96059.72	11.50**	502.26	0.06
Task × Mod	39622.49	4.73*	2.75	0.01
Response (Rsp)	18065.93	3.98	14.12	0.084
Rsp × Mod	207.10	0.05	0.63	0.01
Shape (Shp)	548.22	0.19	56.77	1.29
Shp × Mod	1537.55	0.53	51.91	1.18
Color (Col)	10912.57	5.24**	86.71	1.23
Col × Mod	4427.60	2.12	5.73	0.81
Cue × Task	7638.51	3.52	68.09	0.76
Cue × Task × Mod	4232.56	1.95	0.00	0.00
Cue × Rsp	32053.74	8.53**	0.43	0.01
Cue × Rsp × Mod	90.20	0.02	104.22	2.25
Task × Rsp	53.94	0.02	485.69	15.83***
Task × Rsp × Mod	848.28	0.30	1.65	0.05
Cue × Task × Rsp	3.19	0.01	143.87	3.47
Cue × Task × Rsp × Mod	109.00	0.05	0.73	0.02
Cue × Shp	73.90	0.02	22.51	0.60
Cue × Shp × Mod	12.29	0.01	3.17	0.08
Task × Shp	18185.05	7.88**	67.06	2.07
Task × Shp × Mod	12926.14	2.07	81.78	1.91
Cue × Task × Shp	2211.61	1.15	3.17	0.06
Cue × Task × Shp × Mod	3055.79	1.58	128.43	2.41
Rsp × Shp	67687.88	20.88***	1796.16	22.72***
Rsp × Shp × Mod	10575.27	3.26	953.46	1.21
Cue × Rsp × Shp	17325.00	6.69*	279.58	3.19
Cue × Rsp × Shp × Mod	1754.03	0.68	0.54	0.06
Task × Rsp × Shp	22992.12	7.50**	52.45	0.77
Task × Rsp × Shp × Mod	10603.77	3.46	2.73	0.04
Cue × Task × Rsp × Shp	12650.40	3.33	150.93	2.27
Cue × Task × Rsp × Shp × Mod	3037.72	0.80	0.31	0.01
Cue × Col	1238.03	0.59	4.72	0.07
Cue × Col × Mod	1544.14	0.73	26.39	0.40
Task × Col	471.91	0.14	11.22	0.17
Task × Col × Mod	5920.59	1.72	166.47	2.48
Cue × Task × Col	21904.80	4.24*	37.37	0.59
Cue × Task × Col × Mod	3917.32	0.76	11.85	0.19
Rsp × Col	38252.34	8.98**	3444.50	43.74***
Rsp × Col × Mod	5125.91	1.20	166.48	2.11
Cue × Rsp × Col	5898.45	4.96	75.39	1.15
Cue × Rsp × Col × Mod	6458.24	5.43*	0.20	0.01
Task × Rsp × Col	11255.40	7.12*	60.15	0.95
Task × Rsp × Col × Mod	4054.56	2.57	94.14	1.48
Cue × Task × Rsp × Col	1.54	0.01	67.01	1.06
Cue × Task × Rsp × Col × Mod	386.93	0.15	1.87	0.03
Shp × Col	86.73	0.03	105.09	1.50

Table 4 continued

Effect	RT$_{R2}$		PE$_{R2}$	
	MSE	*F*	MSE	*F*
Shp × Col × Mod	7282.45	2.81	15.94	0.23
Cue × Shp × Col	5044.45	2.89	48.18	1.76
Cue × Shp × Col × Mod	3399.54	1.95	176.13	6.30*
Task × Shp × Col	307.58	0.22	150.94	1.58
Task × Shp × Col × Mod	11.95	0.01	75.03	0.78
Cue × Task × Shp × Col	32.02	0.01	51.97	0.86
Cue × Task × Shp × Col × Mod	113.04	0.04	39.64	0.65
Rsp × Shp × Col	20001.56	6.01*	139.93	2.63
Rsp × Shp × Col × Mod	2085.26	0.63	90.69	1.70
Cue × Rsp × Shp × Col	9098.28	4.99**	4.91	0.09
Cue × Rsp × Shp × Col × Mod	3431.52	1.88	51.23	0.99
Task × Rsp × Shp × Col	3175.98	2.02	44.61	1.21
Task × Rsp × Shp × Col × Mod	1236.04	0.78	93.00	2.53
Cue × Task × Rsp × Shp × Col	514.02	0.17	25.21	0.52
Cue × Task × Rsp × Shp × Col × Mod	3572.78	1.16	16.26	0.34

*df*s 1,34 for all effects

* $p < .05$; ** $p < .01$; *** $p < .001$

with early cues but much reduced with late cues. The three-way interaction of time point, color, and response repetition was further modified by cue modality, indicating that this three-way interaction only occurred with auditory cues. That is, the color-by-response interaction was unaffected by time point with visual cues but decreased from early to late cue presentation with auditory cues.

Finally, there was a three-way interaction of shape, color, and response repetition, which was further modified by a four-way interaction involving the time point of cue presentation. As shown in Fig. 6, early cues produced particularly good performance if stimuli and responses remained identical and, particularly, bad performance if the stimulus remained the same (i.e., if both stimulus features were repeated), but the response changed. This pattern was much reduced if the two stimuli and responses were processed under different tasks sets, that is, with late cues. The observation that exact repetitions of stimulus–response pairings produce particularly good performance has been frequently made in studies on repetition effects since Bertelson (1963). According to Bertelson, this pattern suggests that participants have the tendency to check a new stimulus against a representation of the previous one, and immediately proceed to repeating the last response if the two stimuli match. This is beneficial entirely in typical repetition studies, where repetitions of stimuli necessarily imply the repetition of the response. In our task, however, the relationship between S1 and R1 (which varied randomly) was entirely independent of the relationship between S2 and R2 (which was determined by the instructed mapping), so that the former bore no relevance for the latter. Accordingly, we were able to both replicate the previously reported benefit of complete stimulus repetitions if they happened to go along with response repetitions and demonstrate the downside of this tendency if stimulus repetitions happened to go with response alternations. Hence, our findings provide converging evidence for the considerations of Bertelson (1963). Moreover, our observation that the special status of complete stimulus repetitions and response repetitions or alternations disappears with late cues points to two possible context conditions for Bertelson's pattern. On the one hand, it may be that facing a stimulus event in between S1 and S2, as in the case of a late cue, impairs the episodic memory trace left by S1, so that it can no longer be compared to S2. On the other hand, it may be that the representations of S1 and S2 can be related to each other only if they are processed under the same attentional set, as was the case with early cues. Given the design of our study, we are unable to decide between these two options, which in addition to that are not mutually exclusive either.

The third cluster relates to color repetitions and color–response bindings, which makes it one of the two most relevant clusters for our present purposes. Given the outcome of Experiment 1, we expected that color-repetition effects and interactions of color repetition with the repetition of other features, especially of the response, would be mediated by task—an indication that feature binding was mediated by the attentional set. However, even more important was the question whether this interaction between repetition effects and task would be further modulated by the time point of cue presentation—which would imply that attentional-set effects are targeting feature integration rather than retrieval. Color repetition was involved in a three-way interaction with time point of cue presentation and task. This effect showed that

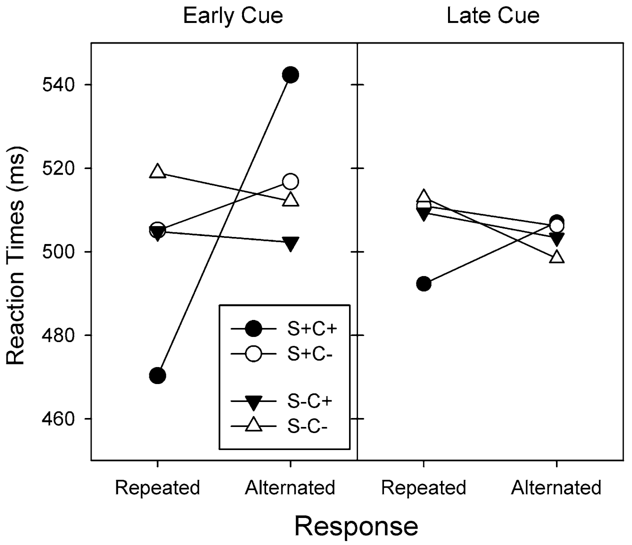

Fig. 6 Experiment 2: Illustration of the four-way interaction between time point of cue presentation and the repetition vs. alternation of stimulus color, stimulus shape, and response. *S* and *C* stand for shape and color, respectively; + and − for repetition and alternation

color repetition facilitated performance if S1 was processed under the color task set: with an early cue signaling a color task (508 vs. 524 ms) but not a shape task (502 vs. 503 ms) and with a late cue signaling a shape task (486 vs. 500 ms) but not a color task (520 vs. 514 ms). Given that we analyzed task alternations only, both early color cues and late shape cues would imply that S1 is processed under a color set. The interaction of color and response repetition was significant, and it was modified by task the same way as it was in Experiment 1 (see Fig. 7). Particularly important, the resulting three-way interaction did not depend on the time point at which the cue was presented, $F < 1$. This was further confirmed by a separate analysis of the data from the late-cue condition only, where both the color–response interaction, $F(1,35) = 19.10$, $\mathrm{MSE} = 2{,}013$, $p < .001$, and the three-way interaction involving task, $F(1,35) = 7.13$, $\mathrm{MSE} = 288$, $p < .05$, were reliable. That is, the effects of color–response binding are modified by the current attentional set even if this set is implemented after the processing of S1 and R1 was completed. In other words, the pattern of the outcomes suggests that the attentional set affects the retrieval, rather than the creation, of event files.

The fourth cluster relates to shape repetitions and shape–response bindings, which makes it the second theoretically relevant cluster. The expectations were analogous to those of the previous, color-related cluster: we expected to replicate the interaction between shape repetition and response repetition, as well as the three-way interaction including these two effects and the task, obtained in Experiment 1. Moreover, we were interested to see whether the three-way interaction would be modulated by the time point of cue presentation. Shape repetitions yielded faster responses than shape alternations in the shape task (493 vs. 503 ms), but not in the color task (520 vs. 513 ms). More difficult to understand was the way this color-by-task interaction was modified by cue modality: whereas visual cues were associated with small repetition benefits in the shape task (465 vs. 470 ms) and the color task (473 vs. 476 ms), auditory cues produced a sizable repetition benefit in the shape task (521 vs. 535 ms) but an alternation benefit of comparable size in the color task (566 vs. 550 ms). More important for our purposes, both the interaction of shape and response repetition and the three-way interaction with task were reliable.[5] As for the color–response bindings, the resulting three-way interaction did not depend on the time point at which the cue was presented, $p = .26$. This was further confirmed by a separate analysis of the data from the late-cue condition only, where the shape–response interaction, $F(1,35) = 3.07$, $MSE = 3{,}371$, $p = .08$, was close to significance and the three-way interaction involving task was reliable, $F(1,35) = 6.76$, $MSE = 3{,}475$, $p = .007$. As for the color–response binding, shape–response binding were modified by the current attentional set even if this set was implemented after the processing of S1 and R1 was completed. Hence, the outcome again suggests that the attentional set affects the retrieval, rather than the creation, of event files. Finally, shape–response bindings were stronger in the auditory modality (42 ms) than in the visual modality (16 ms) and in the early cue (45 ms) compared to late cue (14 ms).

Error rates

The error analysis yielded a few reliable results that in part followed the pattern of the RTs (see Table 4), such as the interactions between color and response and between shape and response. As in RTs, participants also performed worse if the cue was auditory than when it was visual (13.5 vs. 6.1 %). The four remaining effects were not found in RTs. Performance was worse if the cue was early than if it was late (10.7 vs. 9.0 %). This effect was modified by cue modality, indicating that the time-point effect was less pronounced with visual cues (6.4 vs. 5.8 %) than with auditory cues (14.9 vs. 12.2). Moreover, participants performed better if the response was repeated rather than

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[5] Note that there was an anomaly regarding the way task modulated shape/response interactions. With late cues, the interaction of shape and response repetition was pronounced under the shape task and negligible under the color task. This was the expected pattern—a mirror image of the findings for color/response interactions. With early cues, however, the interactions were equally pronounced under both tasks, even though this did not render the related four-way interaction with task and time point significant. We have no explanation for this particular pattern to offer but note that similar asymmetries between perceptual dimensions have been reported before (e.g., Hommel, 1998).

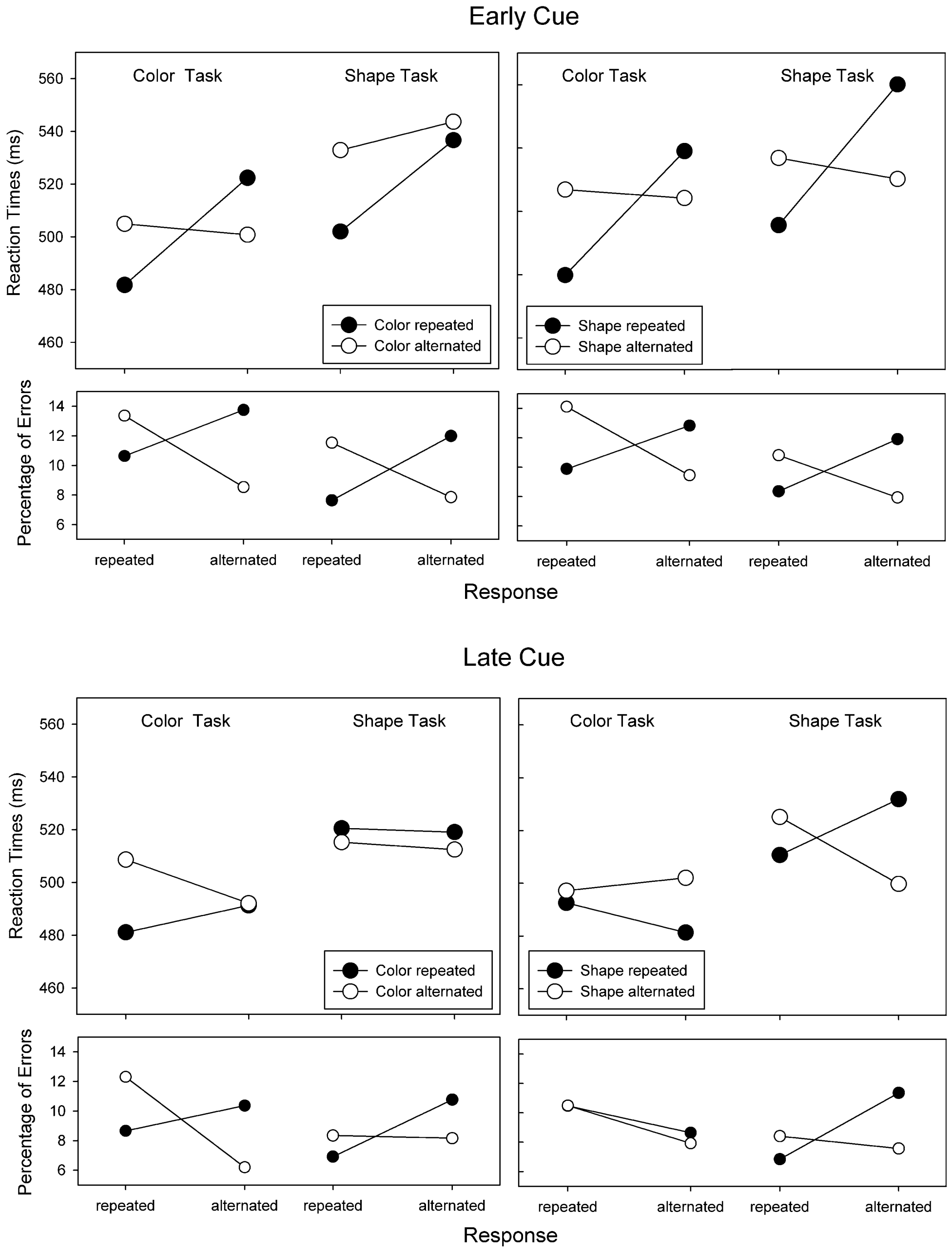

Fig. 7 Reaction times and percentage of errors in Experiment 2 in early cue (*upper panel*) and late-cue trials (*lower panel*), as a function of response repetition, color repetition, and task (*left panels*) and response repetition, shape repetition, and task (*right panels*)

alternated in the color task (8.6 vs. 9.7 %) but showed the opposite pattern in the shape task (11.2 vs. 9.7 %). Finally, there was a four-way interaction involving color and shape repetition, time point of cue presentation, and cue modality (Fig. 7). It indicated that color and shape repetition interacted only with an early presented auditory cue but not with late and/or visual cues. Even though the latter two effects are difficult to interpret, it is important to point out that the error analyses did not provide evidence for any speed-accuracy trade-off that might compromise the interpretation of the RT analysis.

Experiment 2 was conducted to test whether attentional manipulations affect feature integration proper or the repetition-induced retrieval of feature bindings. The findings are clear-cut: Not only did we replicate the observations from Experiment 1, but we also obtained clear evidence that retrieval and not integration is affected by the attentional manipulation. Most relevant for this conclusion are two findings. First, attentional set strongly modulates the color–response and shape–response interactions even if the task cue follows S1 and R1 (see Fig. 7, late cue). As these modulations cannot result from selective integration of S1 and R1 features, they must reflect selective retrieval induced by, and during S2–R2 processing. Second, the modulation induced by late cues is no less powerful than that induced by early cues. In other words, presenting the cue before, rather than after, S1 does not seem to add anything, so that there is no reason to assume that feature integration was modulated in addition to feature retrieval. Again, one might object that participants might have delayed the reconfiguration of their attentional sets until S1 processing was completed, but the observation that the modulations of the color–response and shape–response interactions by the attentional set were the same whether attentional set was repeated or not (see our first analysis) speaks against this possibility. Thus, it is safe to conclude that the attentional manipulation had no impact on feature integration but restricted the retrieval of bindings to those matching the current attentional set.

Conclusions

The first aim of our study was to see how flexible and dynamic attention can control the way feature bindings affect our behavior. Consistent with previous findings, we found that behavior is mostly and mainly affected by bindings between stimulus and response features that are somehow related to the task at hand. The new finding is that this is even true when task relevance changes from trial to trial, suggesting that relevance-related effects are directly and immediately produced by implementing a particular attentional set. Note that this observation goes beyond previous findings of fast and adaptive binding and rebinding of stimulus and response features from trial to trial in showing that these processes are under a relatively tight control of the present attentional set even if that set is frequently modified.

The second aim of the study was to see which processes are controlled by attention. Taken together, our observations strongly favor the retrieval of recent bindings as the target of attentional control. This conclusion calls for a considerable revision of current theorizing about feature integration and has rather interesting broader implications. However, before discussing these issues let us briefly consider whether and how our findings might be affected by nonspecific effects of the late task cues. The time point of cue presentation interacted with numerous effects, and there are various examples where late cues reduced or even eliminated event-file effects. This has decreased the binding-related variance in the late-cue conditions, thus making it more difficult to find binding-related effects. Importantly, however, this must have worked against the retrieval version of our hypothesis and, thus, biased the outcomes toward the integration version (e.g., by increasing the likelihood of interactions between event-file effects and the time point of cue presentation). From that perspective, our conclusion that the outcomes are more consistent with a retrieval hypothesis can be considered rather conservative.

With regard to theory, recent approaches have focused on feature integration as the target of control, assuming that only task-related features are integrated (Hommel, 2004). Our present findings challenge that view and support Logan et al.'s (1996) warning that selective retrieval may lead one to underestimate the amount of information that is encoded. Feature integration proper seems to be nonselective and rather automatic, in the sense that it comprises all features of an event that are coded, independent of whether the integration is necessary or intended or not. The result of integration does not seem to be a single, unitary information folder or instance (in the sense of Logan, 1988) but, rather, a lattice of mostly binary links between stimulus features (e.g., color and shape) and between stimulus and response features (Hommel, 1998; Hommel & Colzato, 2004). Indeed, there is evidence that bindings between stimulus features and bindings between stimulus and response features are mediated by different neurotransmitter systems (Colzato, Fagioli, Erasmus & Hommel, 2005; Colzato & Hommel, 2008). Implementing an attentional set seems to prime task-relevant feature dimensions, which again renders task-relevant features more effective retrieval cues. Accordingly, task-relevant features are more likely to retrieve recent bindings, which explains the pattern of our results.

With regard to wider implications, it is interesting to relate the proposed retrieval view to our observation that retrieval can apparently be biased very quickly (i.e., from trial to trial). Recent studies sought to find out whether trial-to-trial fluctuations of the sizes of compatibility effects are due to executive control functions or episodic retrieval. For instance, Gratton, Coles, and Donchin (1992) observed that the impact of response-compatible and response-incompatible flanker stimuli decreases after incompatible trials, which they explained by assuming that the experience of incompatibility-induced conflict in the previous trial might increase executive control in the current trial. Similar findings have been reported from Simon tasks and they have been explained in a similar fashion (Stürmer, Leuthold, Schröter, Soetens, & Sommer, 2002). However, given that the possible transitions from incompatible (in the previous trial) to compatible or incompatible (in the present trial) on the one hand and from compatible to compatible or incompatible on the other are not equated with respect to partial-overlap conditions, the decrease of compatibility effects after incompatible trials may simply reflect the episodic retrieval of previous bindings. There is indeed evidence that episodic retrieval accounts for at least a large part (Hommel, Proctor & Vu, 2004; Mayr, Awh & Laurey, 2003) but perhaps not all (Ullsperger, Bylsma & Botvinick, 2005; Wühr & Ansorge, 2005) of the effect. Our present findings suggest that attentional control and episodic retrieval may not provide mutually exclusive explanations or represent independently operating mechanisms but, rather, may interact more directly than previously assumed (cf., Spapé & Hommel, 2008). Registering conflict in a given trial may more or less directly increase the strength or activation of the current attentional set (Botvinick, Braver, Barch, Carter & Cohen, 2001), which according to our considerations should facilitate the retrieval of bindings including set-consistent features, and hinder the retrieval of bindings including set-inconsistent features, in the next trial(s). This would mean a reduced impact of flanker-induced retrieval in a flanker task and of location-induced retrieval in a Simon task after conflict trials, which could account for that part of the conflict-adaptation effect that cannot be accounted for by the mere presence of episodic retrieval.

In any case, given the increasing evidence of contributions from episodic retrieval to behavior (Bargh & Ferguson, 2000; Hommel, 2004; Milliken, Tipper & Weaver, 1994), the finding that retrieval seems to be tightly and flexibly controlled by the attentional set opens numerous avenues to improve human performance. One obvious direction would be to attract attention to dimensions that relate to internal or environmental retrieval cues for overlearned procedures. For instance, medication adherence in elderly people and patients should be more successful if the individual is not presented with the common time-based schedule (e.g., three times per day or at particular times) but if the drug-taking action is associated with stimuli that he or she is likely to encounter and attend to at the time the medication is due—hence, if the schedule is event-based rather than time-based (cf., Park & Kidder, 1996). Another obvious direction would be to distract attention from dimensions that are likely to enable retrieval cues for unwanted action tendencies. Successful examples stem from laboratory tasks, where decreasing the task relevance of color words using manual instead of vocal color-naming actions is already known to drastically reduce the impact of Stroop-like color-word distracters (Keele, 1972), and from everyday problems like intrusive thoughts about dramatic events, which are easier to inhibit if attending to feature dimensions that are unrelated to that event.

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