

# How Much Attention Does an Event File Need?

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Attentional requirements for the spontaneous integration of stimulus and response features were analyzed. In line with previous findings, carrying out a prepared response to the onset of a stimulus created bindings between the response and the features of that stimulus, thereby impairing subsequent performance on mismatching stimulus–response combinations. Findings demonstrate that a stimulus gets bound to a response even if its presence is neither necessary nor useful for the task at hand, it follows rather than precedes the response in time, it competes with a task-relevant stimulus, and if the response is suppressed—but only if the stimulus appears close to the response’s eventual execution or abandonment. A multiple-integration model is suggested that assumes that the integration of stimulus features in perception and of response features in action planning are local processes that are independent of stimulus–response integration, which presumably is triggered by the success of the perception-action episode.

*Keywords:* feature integration, binding problem, episodic retrieval, attentional set

The human brain codes perceptual events and action plans in a distributed fashion. That is, perceiving any given stimulus involves the activation of a large number of neural codes representing its features (DeYoe & Van Essen, 1988), and setting up an action plan involves the recruitment of numerous neural codes specifying the features of the intended action (Stoet & Hommel, 1999; Wickens, Hyland, & Anson, 1994). Distributed representation and processing are likely to create binding problems that call upon mechanisms of feature integration (Roskies, 1999; Treisman, 1996). That is, perceiving and acting are likely to induce or even require binding the codes of the features of the perceived or to-be-produced event into some transient, coherent structure—a kind of object file (Kahneman, Treisman, & Gibbs, 1992) or, in more general terms, event file (Hommel, 1998, 2004).

One way to investigate the existence, creation, and lifetime of event files is to study their impact on subsequent processes. As observed by Kahneman et al. (1992), Henderson (1994), and others, processing a reviewed visual object, Stimulus 1 (S1) → Stimulus 2 (S2), is easier if its features are combined exactly the same way as during the previous encounter. For instance, identifying a letter presented at a particular location is easier if this letter occupied the same location when it was seen before. This suggests that processing an object involves or leads to a binding between codes of its shape and location so that, when one of these features is encountered again, the whole binding is reactivated, which

benefits performance if the new feature conjunction matches the old conjunction but impairs performance if the feature overlap is incomplete (Hommel, 2004).

Event files not only integrate visual features but also seem to bind stimulus features to responses or, perhaps more precisely, to response features. Take the example of the Hommel (1998) study, which used a design very similar to the one used in the present study (see Figure 1). Participants performed sequences of a simple reaction time (RT) task followed by a binary-choice RT task. In each trial, a precue indicated whether the first response (R1) was to be a left- or a right-hand keypress. R1 was to be withheld until the next upcoming stimulus (S1) appeared and then carried out independently of any particular feature of S1. One second later, another stimulus (S2) was presented, with its shape (e.g., letter *O* vs. *X*) signaling a speeded manual left–right response. The shape, color, and location of S1 and S2 varied independently, as did R1 and Response 2 (R2). Apart from interactions between shape and location repetitions along the lines of Kahneman et al. (1992), the repetition or alternation of stimulus features interacted with response repetition. For example, response repetitions were faster and more accurate if stimulus shape (or stimulus location) was also repeated than if shape (or location) alternated, whereas response alternations were faster and more accurate if shape (or location) alternated than if shape (or location) was repeated. In other words, repeating both stimulus (features) and response yields performance that is as good as if stimulus and response are both changed. This suggests that the effect indicates not so much the benefit from repeating a stimulus–response (S-R) conjunction but the cost incurred by an only partial overlap between previous and current event files. That is, any feature overlap seems to reactivate the previously created event file, which induces stimulus and/or response conflict if that file includes competing stimulus or response codes (Hommel, 2004).

The present study sought to explore the attentional demands of event file creation, with a particular focus on feature integration across stimulus and response domains. At one extreme, event files might be created fully automatically, that is, the cognitive system

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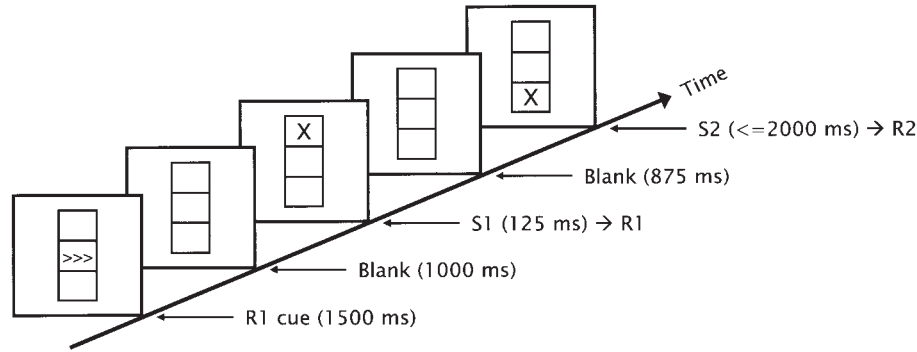


Figure 1. Basic experimental setup. The two subtasks consist of a simple, previously cued go response to Stimulus 1 (S1) and a binary-choice response to the shape of Stimulus 2 (S2). R1 = Response 1; R2 = Response 2; X = stimulus; >>> = response cue.

may store any S-R episode it processes to a minimal degree. Although not much evidence on this issue is available, this possibility is likely to be incorrect. This is suggested by Hommel's (1998) observation that manipulating the task relevance of a stimulus feature affects the probability that it is involved in a binding-related effect. In particular, making shape the critical feature for the second of two succeeding responses (i.e., for the S2 → R2 part of an S1 → R1, S2 → R2 sequence; see Figure 1) leads to a strong interaction between shape repetition and response repetition but not of color repetition and response repetition (suggesting the creation of shape-response but not color-response bindings during S1 → R1 processing), whereas making color the critical feature reverses the outcome pattern. Apparently, features on dimensions that are of some relevance for the task are primed to a degree that makes them more likely to be considered for integration into an event file (Hommel, 2004).

At the other extreme, only features from fully attended events may be integrated. This possibility is also likely to be incorrect for at least two reasons. First, the very fact that task relevance has an impact on feature integration demonstrates that all features of an event are not equal. That is, even if one would be willing to argue that responding to the mere onset of a stimulus, as in Hommel's (1998) study, necessitates some degree of "attention" devoted to S1 processing, this apparently does not guarantee that all features of the attended stimulus are integrated. Hence, attending to an event is not sufficient for binding. Second, explicitly drawing attention to the features of the to-be-integrated stimulus (S1) by having participants report them after each trial has little impact on a feature's likelihood to be integrated (Hommel & Colzato, 2004). Hence, endogenous focusing of attention on an event does not seem to be necessary either.

Taken altogether, the available evidence shows that processing a visual object or performing a prepared, unrelated response to the onset of a visual event leads to the creation of visuo-visuo and visuo-manual bindings or event files. Event-file creation is not fully automatic, as task-relevant features are more likely to be integrated than are task-irrelevant features, but it at the same time does not seem to draw upon considerable amounts of attentional resources. The aim of the present study was to explore the theoretical space left between these two constraints, that is, to provide tighter empirical constraints for defining the necessary and sufficient conditions underlying feature binding. This was done by

actively discouraging participants from attending and processing the critical stimulus event (a visual S1, in the S1 → R1, S2 → R2 design of Hommel, 1998) and by introducing increasingly taxing task demands that are likely to leave fewer resources to S1 processing. The crucial question was, then, whether these manipulations would reduce or even eliminate the binding of stimulus and response features.

A useful way to divert attention from a particular event is to introduce other stimulus events that are relevant to the task and, thus, call for attention. This was the rationale underlying the present Experiments 4 through 8. In general, participants encountered sequences of two visual events and two manual responses (S1 → R1, S2 → R2; see Figure 1), just as in Hommel's (1998) original setup. However, whereas the visual S2 signaled R2 (which in all experiments made shape the relevant S2 feature and location the relevant R2 feature), the visual S1 was entirely irrelevant to the degree that even its presence did not have to be noticed. Instead, participants were cued to prepare R1 (in most experiments), a left or right keypress, which they carried out to the onset of a tone that temporally overlapped or was close to but did not covary with the visual S1 (cf. Hommel, Proctor, & Vu, 2004). The question thus was whether the features of S1 and R1 would be integrated (as measured by the impact of this integration on S2 → R2 performance) even though R1 was actually carried out in response to another stimulus. These manipulations introduced some factors that might affect feature binding in other ways than intended. For reasons elaborated later, presenting a tone might affect feature binding by increasing cortical arousal, and changing the temporal relation between S1 and R1—which is unavoidable if R1 is actually a response to another stimulus—might impair their integration. To get a handle on these factors, Experiments 1 through 3 were carried out to test the impact of the mere presence of tones close to a visual S1 and of the temporal relationship between S1 and R1.

## Experiment 1

Most of the experiments in this study used tones to signal R1, which was thought to work against the processing of the visual S1. However, tones are likely to increase the arousal level of the central nervous system (Näätänen, 1992), which might affect feature integration. Indeed, there is evidence that the binding of

stimulus features is sensitive to drugs that stimulate the muscarinic part of the cholinergic system (Colzato, Erasmus, & Hommel, 2004; Colzato, Fagioli, Erasmus, & Hommel, 2005). Even though these modulations indicate the impact of tonic rather than phasic increases of arousal, some connection between arousal and integration does seem to exist. If so, introducing tones might not only draw attention away from the visual S1, which is the intended effect, but also exert some direct impact on feature binding, which would complicate the interpretation of possible differences from the findings obtained with the standard experimental setup. To evaluate this possibility, in Experiment 1 I compared the standard setup as used by Hommel (1998) with an otherwise identical version in which the visual S1 was accompanied by a task-irrelevant tone. To avoid tone-related strategies, I intermixed the two versions, that is, tones appeared randomly and unpredictably. Participants worked through a close replication of Hommel's (1998) task, with shape as relevant S2 feature and a visual S1 that was accompanied by a tone in a random half of the trials. Two stimulus features were varied (shape and location), and the response consisted of a left-versus-right keypress. In view of the available findings, this setup was expected to produce interaction effects between the repetition (vs. alternation) of shape and response location (presumably indicating shape–response binding) and between the repetition of stimulus location and response location (indicating location–response binding)—apart from a possible, but often weak interaction between the two stimulus features involved (indicating within-domain shape–location binding).

## Method

**Participants.** Twelve adults were paid to participate in single sessions of about 50 min. They reported having normal or corrected-to-normal vision and audition and were not familiar with the purpose of the experiment.

**Apparatus and stimuli.** The experiment was controlled by a standard PC, attached to a 17-in. (about 43-cm) color monitor. Participants faced three gray square outlines, vertically arranged, as illustrated in Figure 1. From the viewing distance of about 60 cm, each of these frames measured about  $1.2^\circ \times 1.2^\circ$ . The letters *O* and *X*, taken from the standard text font, served as S1 and S2 alternatives, which were presented in the top or bottom frame. The response cue appeared in the middle frame (see Figure 1), with rows of three left- or right-pointing arrows indicating a left and right keypress, respectively. The auditory stimulus was a 200-Hz sinusoidal tone presented for 50 ms. Responses to S1 and S2 were made by pressing the left or right shift-key of an external keyboard with the corresponding index finger. Errors were fed back with a short beep.

**Procedure and design.** Participants carried out two speeded 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 shape or location and independent of the tone. 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's attributes. R2 was a binary-choice reaction with the left or right key to the shape of S2. Half of the participants responded to the *O* and the *X* by pressing the left and right key, respectively, whereas the other half received the opposite mapping.

The sequence of events in each trial is shown in Figure 1. Following the intertrial interval of 2,000 ms, a response cue signaled R1 for 1,500 ms, followed by a blank interval of 1,000 ms. Then S1 appeared for 125 ms, followed by a further blank interval of 875 ms. In half of the trials S1 was accompanied by a tone (0-ms onset asynchrony between the tone and S1). If R1 was incorrect, anticipatory (RT < 130 ms), or not given within 1,000

ms (counted as omission) the trial started from the beginning. After the blank interval, S2 appeared and stayed until R2 was given or 2,000 ms had passed—the stimulus onset asynchrony (SOA) between S1 and S2 was thus 1,000 ms. Responses to S2 that were incorrect, premature (RT < 130 ms), or omitted (RT > 2,000 ms) were stored and repeated at a randomly chosen position of the remainder of the given block.

Apart from 20 randomly determined practice trials at the beginning, each session comprised four 64-trial blocks, amounting to a total of 256 valid trials. Each block was composed by a factorial combination of the two shapes (*O* vs. *X*) and two locations (top vs. bottom) of S2; the repetition versus alternation of shape, location, and response; and the presence versus absence of the tone ( $2 \times 2 \times 2 \times 2 \times 2 \times 2 = 64$ ). The trials within a block were randomly ordered. Participants could take a break after each block.

## Results

The first, precued response (R1) was carried out in 325 ms, on average; errors were rare (0.7%), as were anticipations (1.8%) and response omissions (1.0%). After excluding trials in which R2 was anticipated (1.8%) or omitted (0.03%), percentages of errors on R2 and mean RTs from error-free R2s were calculated as a function of repetition versus alternation of stimulus shape and location, repetition versus alternation of the response, and the presence versus absence of the tone (see Table 1).

The RTs produced a main effect of response repetition,  $F(1, 11) = 5.97$ ,  $MSE = 2,614$ ,  $p < .05$ , that was modified by two-way interactions with shape repetition,  $F(1, 11) = 44.47$ ,  $MSE = 1,030$ ,  $p < .001$ , and with stimulus-location repetition,  $F(1, 11) = 21.53$ ,  $MSE = 904$ ,  $p < .001$ . As Figure 2 shows, repeating a response produces better performance than alternation if, and only if, the respective stimulus feature (shape or location) is also repeated. If it is not, the repetition effect turns into a relative alternation benefit. Of importance, neither of these interactions was modified by tone ( $p > .36$  and  $p > .20$ ). The interaction of shape and location repetition missed the significance criterion ( $p < .17$ ). Figure 3 summarizes the relevant RT effects by indicating the sizes of the three feature-related two-way interactions<sup>1</sup>—an intuitive representation of the amount of feature integration—as a function of tone presence.<sup>2</sup>

The percentages of errors revealed a similar pattern to the RTs: Apart from a main effect of location repetition,  $F(1, 11) = 6.90$ ,  $MSE = 17.26$ ,  $p < .05$ , the two-way interactions of Shape Repetition  $\times$  Response Repetition,  $F(1, 11) = 18.46$ ,  $MSE = 48.57$ ,

<sup>1</sup> Interaction effects for two given features *X* and *Y* were calculated by subtracting the RTs for complete repetitions and “complete” alternations (both *X* and *Y* repeated or both *X* and *Y* alternated) from the RTs for partial repetitions (*X* repeated and *Y* alternated, or vice versa). That is, if features *X* and *Y* repeated and alternated, their interaction effect  $IAE_{XY}$  would be  $IAE_{XY} = (RT_{X/alt, Y/rep} + RT_{X/rep, Y/alt}) / 2 - (RT_{X/rep, Y/rep} + RT_{X/alt, Y/alt}) / 2$ , where *alt* refers to alternation and *rep* refers to repetition. These effects thus correspond to the two-way interaction term of the respective features; a value close to zero means that the repetition effects of the two given features do not interact; a value greater than zero indicates a “bindings-type” interaction of the sort described in the text.

<sup>2</sup> Confidence intervals for interactions between two given factors *X* (e.g., shape) and *Y* (e.g., location) were computed by using the mean-square-error term from one-way within-subjects analyses of variance with factor *Y* (e.g., location repeated vs. alternated) on the individual difference scores on factor *X* (e.g., shape alternation minus shape repetition, for each level of location; see Masson & Loftus, 2003, p. 212).

Table 1  
Means of Mean Reaction Times for Responses to Stimulus 2 ( $RT_{R2}$ ; in Milliseconds) and Percentages of Errors on Response 2 ( $PE_{R2}$ ) in Experiment 1

Match	Without tone				With tone			
	$RT_{R2}$		$PE_{R2}$		$RT_{R2}$		$PE_{R2}$	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Neither	459	88	0.0	0.0	458	95	1.0	2.3
Shape (S)	480	122	1.5	2.7	490	127	2.8	4.9
Location (L)	487	91	2.8	4.5	497	87	5.4	6.9
Response (R)	521	92	8.1	9.2	534	97	9.3	7.6
SL	480	68	8.0	7.1	525	114	13.1	10.4
SR	491	116	1.5	2.7	493	103	2.0	2.9
LR	515	87	3.7	8.2	527	97	3.2	5.4
SLR	464	110	1.9	3.7	475	121	0.5	1.7

Note. Values shown are as a function of absence or presence of tone and the feature match between the shape and location of Stimulus 1 and Stimulus 2 and the match between Response 1 and Response 2.

$p < .001$ , and of Location Repetition  $\times$  Response Repetition,  $F(1, 11) = 14.26$ ,  $MSE = 66.38$ ,  $p < .005$ , were reliable, and neither interaction was modified by tone ( $p > .53$  and  $p > .74$ ). Figure 2 shows that the error rates mirrored the RTs. In contrast to the RTs, the error rates yielded a significant interaction of shape and location repetition,  $F(1, 11) = 18.98$ ,  $MSE = 14.26$ ,  $p < .001$ , which, however, went in the opposite direction to the RTs and, thus, may reflect a speed-accuracy trade-off.

Discussion

For the most part, the findings nicely replicate previous observations. In particular, the effect of response repetition was clearly dependent on whether stimulus features are repeated or not, suggesting that the co-occurrence of the shape and the location of S1 was integrated with R1 (Hommel, 1998). As the often small size of

this effect would lead one to expect, the Shape  $\times$  Location interaction was not quite reliable, but its pattern and numerical size is comparable to that obtained in other studies (e.g., Hommel, 1998; Hommel & Colzato, 2004) and the other experiments of the present study. Most important for present purposes, however, was the lack of a reliable indication that the presence of a tone would matter. Thus, there is no reason to assume that facing a tone as such has a (strong) impact on the degree or likelihood of visuo-manual feature integration.

Experiment 2

The rationale underlying this study was to divorce the mere presence of a visual S1 from any task-related function. To do so requires the introduction of another stimulus to trigger the prepared R1, a tone in this case. However, having participants respond

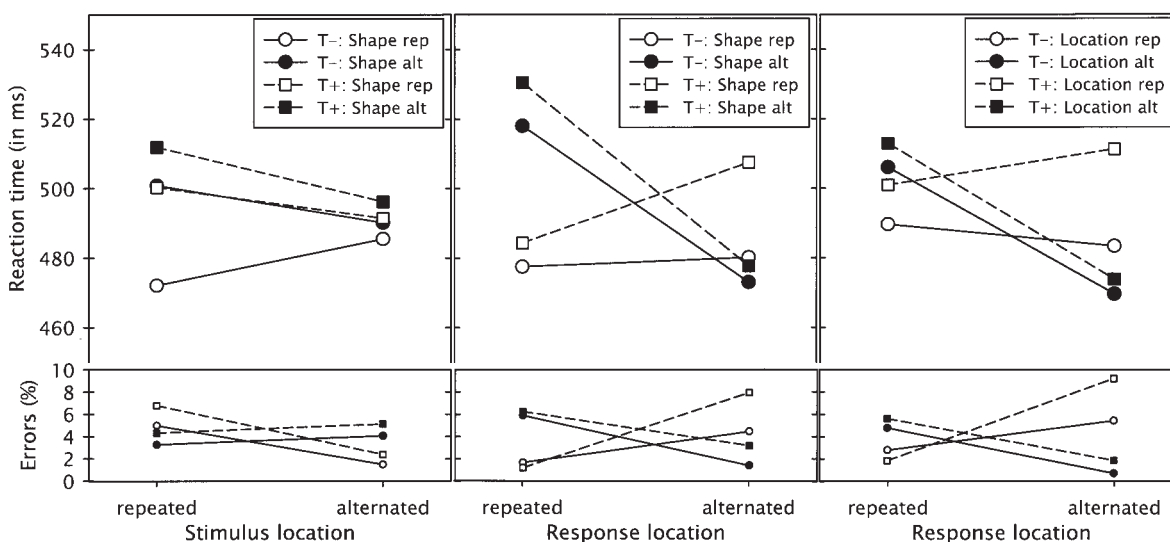


Figure 2. Reaction times and error rates in Experiment 1 as a function of the absence (T-) or presence (T+) of a tone and the match versus mismatch of stimulus shape and stimulus location (left panel), of stimulus shape and response location (center panel), and of stimulus location and response location (right panel). rep = repeated; alt = alternated.

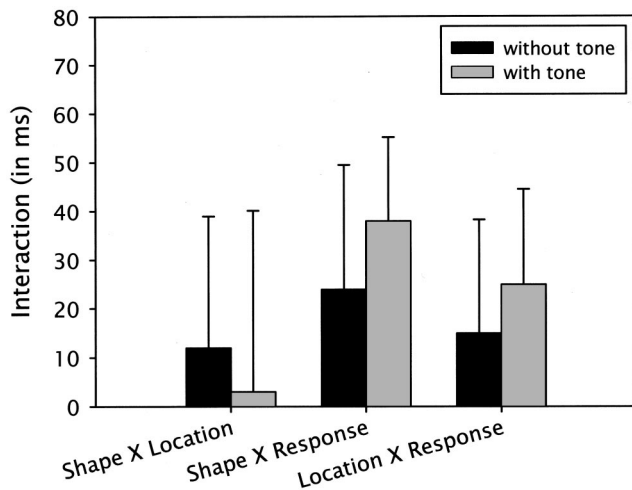


Figure 3. Sizes of two-way interaction effects in the reaction times in Experiment 1 as a function of temporal order of Stimulus 1 and Response 1. Error bars indicate confidence intervals for the corresponding interaction effects.

to a tone instead of a visual stimulus is likely to change the speed of responding: Tones commonly take less time to detect than visual signals, especially in a sequence of otherwise visual stimuli. This changes the temporal relationship between the visual S1 and the now tone-triggered R1, which may affect, perhaps weaken, the likelihood, degree, or strength of S1-R1 integration for reasons other than the attention S1 has received. Experiments 2 and 3 were conducted to explore how serious this problem might be.

Experiment 2 was a close replication of the no-tone variant of Experiment 1 with one little twist: In one block of trials the visual S1 signaled the execution of R1, as usual, but in another block S1 was triggered by R1. That is, the usual sequence of S1 → R1 was now reversed to R1 → S1. This manipulation may produce two different outcomes. On the one hand, the integration of stimulus and response features might be restricted to unidirectional sequences of stimuli followed by responses, perhaps even to sequences within a limited time interval. If so, we would expect a replication of the findings of Experiment 1 in the S → R condition but not in the R → S condition. On the other hand, the temporal integration window for feature integration might be rather broadly defined, so that any feature code activated within a rather extended time interval would be bound to the same event file. The findings of Hommel et al. (2004) suggest that this is a serious possibility: They obtained evidence that manual responses are bound to the location of stimuli presented at a point in time that was close to the average RT. Along these lines one would expect comparable binding effects under S → R and R → S conditions.

### Method

Twelve adults participated; they all fulfilled the same criteria as applied in Experiment 1. The method was as in Experiment 1, with the following exceptions. The response cue appeared for 2,000 ms. In one part of the session (S → R condition), the sequence of events was very similar to Experiment 1: The response cue was followed by a blank interval of 500 ms, the presentation of S1 for 500 ms, another blank interval of 500 ms, and the usual presentation of S2 until R2 or 2,000 ms had passed. Participants were to prepare R1 upon presentation of the response cue, carry it

out in response to S1 onset, and then react to the shape of S2. As in Experiment 1, the SOA between S1 and S2 was 1,000 ms. In another part of the session (R → S condition), R1 was to be carried out to the offset of the response cue. In the case of a correct R1, S1 appeared as soon as R1 was registered and stayed for 500 ms, followed by a blank interval of 500 ms. Again, the SOA between S1 and S2 was always 1,000 ms. Apart from the error beep, no tones were presented. The order of the two parts of the session was balanced across participants. Each part was comprised of five 32-trial blocks, with the first being treated as practice. Each block was composed by a factorial combination of the two shapes (O vs. X) and two locations (top vs. bottom) of S2 and the repetition versus alternation of shape, location, and response.

### Results

R1 was carried out in 339 ms, on average; errors were rare (0.7%), as were anticipations (1.4%) and response omissions (0.4%). After excluding trials in which R2 was anticipated (0.7%) or omitted (0.005%), R2 data were analyzed as a function of shape and location repetition, response repetition, and temporal order (see Table 2).

The RTs yielded main effects of temporal order,  $F(1, 11) = 4.82$ ,  $MSE = 5,180$ ,  $p < .05$ , and shape repetition,  $F(1, 11) = 5.34$ ,  $MSE = 3,643$ ,  $p < .05$ . Shape repetition interacted with location repetition,  $F(1, 11) = 21.52$ ,  $MSE = 846$ ,  $p < .001$ , and with response repetition,  $F(1, 11) = 42.71$ ,  $MSE = 1,302$ ,  $p < .001$ , and location repetition interacted with response repetition,  $F(1, 11) = 26.77$ ,  $MSE = 390$ ,  $p < .001$ . Of importance, all higher order interactions were far from significance ( $p > .20$ ). Separate analyses confirmed that all three interactions were reliable under either temporal order ( $ps < .05$ ), except for the Location × Response interaction, which only approached significance in the R → S condition ( $p = .077$ ). Figure 4 summarizes the relevant interaction effects as a function of temporal order.

The error rates revealed a main effect of shape repetition,  $F(1, 11) = 5.82$ ,  $MSE = 25.55$ ,  $p < .05$ , that was modified by response repetition,  $F(1, 11) = 36.71$ ,  $MSE = 24.77$ ,  $p < .001$ . This effect, which separate analyses confirmed to be reliable under each temporal order ( $p < .05$ ) indicated that repeating a response produced fewer errors than alternation if shape was also repeated (2.9% vs. 5.6%) but more errors if shape alternated (9.0% vs. 3.0%). The interaction of location repetition and response repetition just missed the significance criterion ( $p < .06$ ).

### Discussion

The results are clear in replicating all three feature-related two-way interactions. Most important, none of these effects were modulated by the manipulation of temporal order, which suggests that the integration of stimulus and response features uses a rather broad time window of at least  $\pm 0.5$  s. Moreover, the observation that temporal order has no reliable impact (within the range used here) suggests that the integration of stimulus features and response features does not require that the response be made to that stimulus. Rather, what counts seems to be the mere co-occurrence of the two events within a particular time window.

### Experiment 3

Experiments 1 and 2 provided no evidence that the presence of a tone, as such, affects the integration of a visual S1 and a manual

Table 2  
Means of Mean Reaction Times for Responses to Stimulus 2 ( $RT_{R2}$ ; in Milliseconds) and Percentages of Errors on Response 2 ( $PE_{R2}$ ) in Experiment 2

Match	Stimulus 1 → Response 1				Response 1 → Stimulus 1			
	$RT_{R2}$		$PE_{R2}$		$RT_{R2}$		$PE_{R2}$	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Neither	418	50	0.5	1.7	442	95	2.2	5.1
Shape (S)	451	54	2.4	3.8	473	84	4.4	3.5
Location (L)	460	56	4.3	7.8	478	69	5.2	5.0
Response (R)	486	63	8.4	9.6	484	88	7.8	8.5
SL	452	63	10.2	9.2	480	78	5.5	6.2
SR	441	57	4.2	4.8	460	56	5.4	6.9
LR	488	54	8.6	8.6	509	107	11.2	8.1
SLR	392	54	0.5	1.7	446	52	1.4	3.5

Note. Values shown are as a function of the sequence of Stimulus 1 and Response 1 and the feature match between the shape and location of Stimulus 1 and Stimulus 2 and the match between Response 1 and Response 2.

R1, as measured by its impact on S2-R2 performance, and suggest that the features belonging to S1 and R1 are integrated across a rather broad temporal integration window. However, in both experiments R1 was still triggered by a visual event, even though the particular features of S1 were not important. This may have made it difficult or impossible to ignore S1 altogether, or at least not have motivated participants to do so. In Experiment 3, R1 was triggered by a tone, so that the visual S1 was both entirely irrelevant to the task and presented in a different modality than the actual R1 trigger. As another check for a possible impact of the temporal relation between S1 and R1 on S1-R1 integration, S1 preceded or followed the trigger tone by 500 or 250 ms or coincided with it (0 ms). As in Experiment 2, the question was whether the three integration-related interaction effects would occur at all and whether they would vary with the SOA between S1 and tone.

### Method

Twelve adults participated; they all fulfilled the same criteria as applied in Experiment 1. The method was as in Experiment 1, with the following

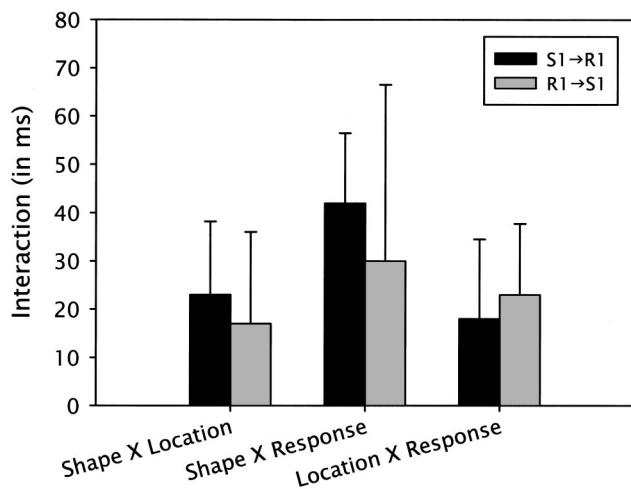


Figure 4. Sizes of two-way interaction effects in the reaction times in Experiment 2 as a function of temporal relation between Stimulus 1 (S1) and Response 1 (R1). Error bars indicate confidence intervals for the corresponding interaction effects.

exceptions. Participants were again to prepare the R1 precued by the response cue, but now they were to perform it in response to the tone (50 ms, 500 Hz). The tone always appeared 1,000 ms after response cue offset and 1,000 ms before S2 onset, just as S1 in Experiment 1. In one session, the tone was accompanied (SOA = -0 ms) or preceded (SOA = -250 or -500 ms) by a 125-ms display of an *O* or an *X* in the top or the bottom box. In another session, the tone was accompanied (SOA = 0 ms) or followed (SOA = 250 or 500 ms) by such a display. In other words, the S1 used in Experiment 1 appeared briefly before, simultaneously with, or briefly after the tone. However, as the tone was to trigger R1, the visual S1 was no longer relevant to the task, and its features had no predictive value anyway. For the sake of terminological consistency, I nevertheless continue to call the visual display *S1* and refer to the tone as *R1 trigger*, if necessary. According to this terminology, S1 and R1 trigger were identical in Experiment 1 and in the S-R condition of Experiment 2, but they differed in Experiment 3 (and the remaining experiments). Each participant served in two separate sessions. In one session, the SOAs varied between -500 and 0 ms and in the other they varied between 0 and 500 ms. Hence, the 0-ms SOA condition was run twice, and I call it -0 and 0, respectively. The order of the session was balanced across participants. Each session was composed of 20 randomly drawn practice trials and four 96-trial blocks. Each block was composed by a factorial combination of the two shapes (*O* vs. *X*) and two locations (top vs. bottom) of S2; the repetition versus alternation of shape, location, and response; and the three used SOAs.

### Results

R1 was carried out in 296 ms on average; errors were rare (0.6%), as were anticipations (1.7%) and response omissions (0.2%). After excluding trials in which R2 was anticipated (0.6%) or omitted (0.1%), R2 data were analyzed as a function of shape and location repetition, response repetition, and SOA (see Table 3).

In RTs (see Figure 5), the only reliable effects were the two-way interactions of Shape Repetition × Response Repetition,  $F(1, 11) = 80.55$ ,  $MSE = 1,184$ ,  $p < .001$ , and Location Repetition × Response Repetition,  $F(1, 11) = 18.77$ ,  $MSE = 1,712$ ,  $p < .001$ , whereas the interaction of Shape Repetition × Location Repetition missed the significance criterion,  $F(1, 11) = 2.44$ ,  $MSE = 1,750$ ,  $p < .15$ . The impact of SOA on Shape Repetition × Response Repetition only reached the 12% level, and all other higher order interactions were far from significance ( $p > .25$ ). Separate analyses of variance (ANOVAs) for the six SOA levels revealed that the Shape × Response interaction was reliable for all SOA levels

Table 3  
Means of Mean Reaction Times for Responses to Stimulus 2 ( $RT_{R2}$ ; in Milliseconds) and Percentages of Errors on Response 2 ( $PE_{R2}$ ) in Experiment 3

Match	-500		-250		-0		+0		+250		+500													
	$RT_{R2}$		$PE_{R2}$		$RT_{R2}$		$PE_{R2}$		$RT_{R2}$		$PE_{R2}$													
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD												
Neither	525	140	0.9	3.2	501	126	0.0	0.0	505	116	0.5	1.7	482	110	0.0	0.0	467	59	0.5	1.7	466	76	0.0	0.0
Shape (S)	530	112	1.5	2.7	515	119	1.0	2.3	535	118	2.4	3.8	498	97	3.7	5.8	502	107	2.3	4.8	504	96	0.5	1.7
Location (L)	526	114	1.0	2.3	502	82	2.0	2.9	531	113	1.0	2.3	505	89	0.0	0.0	493	96	1.0	2.3	488	51	0.5	1.7
Response (R)	523	131	2.0	2.9	537	126	2.9	3.8	560	129	2.3	4.8	524	90	1.5	2.7	506	70	5.7	7.7	522	76	1.5	2.7
SL	540	138	1.4	3.5	541	156	1.0	2.3	569	154	2.4	3.8	507	88	4.2	4.8	512	89	3.8	4.8	509	93	3.5	7.0
SR	522	118	2.9	3.8	535	142	1.9	3.7	531	119	1.9	3.7	481	72	1.3	4.6	491	110	1.5	2.7	501	86	0.0	0.0
LR	528	113	1.9	3.7	530	118	4.6	5.6	552	114	1.0	2.3	508	86	2.9	3.1	516	100	3.9	2.9	518	56	1.9	3.7
SLR	495	118	1.4	3.5	496	118	0.5	1.7	506	151	1.5	2.7	479	90	1.0	2.3	462	92	1.9	3.7	476	90	2.4	3.8

Note. Values shown are as a function of stimulus onset asynchrony and the feature match between the shape and location of Stimulus 1 and Stimulus 2 and the match between Response 1 and Response 2.

( $p < .05$ ), and the Location  $\times$  Response interaction was significant for all but the most negative SOA for each session, that is, for the -500-ms condition ( $p = .11$ ) and the 0-ms condition ( $p = .16$ ).

The error rates produced a main effect of location repetition,  $F(1, 11) = 4.97$ ,  $MSE = 3.35$ ,  $p < .05$ , and an interaction between shape repetition and response repetition,  $F(1, 11) = 18.60$ ,  $MSE = 15.72$ ,  $p < .001$ , that followed the same pattern as the RTs. The three-way interaction involving SOA missed significance ( $p < .09$ ). Separate ANOVAs showed that the Shape  $\times$  Response interaction was reliable for the -250-ms, the 0-ms, and the 250-ms conditions ( $p < .05$ ) and approached significance in the -0-ms condition ( $p = .11$ ) and the 500-ms condition ( $p = .14$ ) but was far from significance in the -500-ms condition ( $F < 1$ ).

Discussion

Apart from the fact that the Shape  $\times$  Location interaction was again too weak to reach significance (although it shows the com-

mon pattern), the outcome was expected, that is, S-R integration seems to have taken place. Moreover, the size of integration effects was comparable with those obtained in Experiments 1 and 2. This is remarkable given that participants could ignore the visual S1 altogether—both its features and its presence—and were attending to another sensory channel. This observation adds to Hommel et al.’s (2004) finding that having R1 triggered by a tone does not prevent the integration of the locations of S1 and R1 (which there varied on the same, horizontal dimension). What is more, increasing the temporal distance between S1 and R1 does not significantly affect the likelihood, degree, or strength of integration. It is true that higher order interaction of shape and response with SOA approached significance in both RTs and errors and that the separate analyses showed that the Shape  $\times$  Response interaction was not reliable for all SOAs. However, rather than showing a systematic (e.g., negative) relation between the size of the SOA and the integration effect, these interactions point to an effect of SOA set. That is, the most positive (or least negative) SOA in each

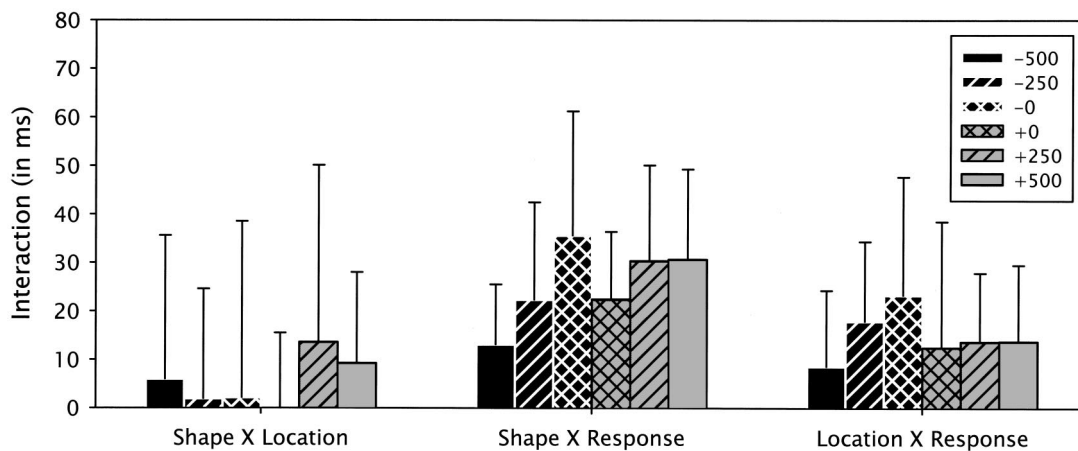


Figure 5. Sizes of two-way interaction effects in the reaction times in Experiment 3 as a function of temporal relation (stimulus onset asynchrony) between Stimulus 1 and Response. Negative and positive asynchrony values indicate that Stimulus 1 led or followed Response 1, respectively. The zero condition was tested twice: blocked with negative asynchronies (-0) and blocked with positive asynchronies (0). Error bars indicate confidence intervals for the corresponding interaction effects.

of the two SOA blocks tended to produce the largest integration effect, irrespective of what that particular SOA was; among other things, this is obvious when comparing the differences between the 0-SOA conditions in the two blocks. Whatever the cause of this tendency might have been, these findings do not suggest a strong reliance of S-R feature integration on temporal overlap of stimulus and response.

#### Experiment 4

Experiment 3 suggests that S-R integration does not require that the stimulus involved is attended or relevant to the task in any sense. However, the processing demands at the time S1 was presented were not overly high either: The relevant stimulus was a salient, easy-to-detect tone, and S1 was the only visual event around, a situation that is unlikely to exhaust the available attentional resources. According to Lavie (1995), processing irrelevant information is more likely the less capacity is occupied by processing the relevant information, which might suggest that an irrelevant S1 is integrated only because the R1 trigger tone was so undemanding to process. If so, increasing the attentional load associated with processing the trigger tone should work against S1 integration. This was the rationale underlying the following experiments. Here, in Experiment 4, participants were again asked to prepare R1 in advance and withhold it until the trigger tone appeared. However, this time, two different tones were used, only one being the instructed go signal and the other a no-go signal in the case of which R1 was not to be carried out. One question was whether this would decrease or eliminate the integration of S1 and R1 features. Another, theoretically interesting question was whether planning but not performing R1, as in the no-go trials, would suffice to create S1-R1 bindings. Following Stoet and Hommel (1999), planning an action involves the recruitment and integration of codes representing the features of the intended action. Even though some additional processes may be necessary to transform an action plan into actual performance, and even if this process might further facilitate S-R integration, planning may be sufficient to activate action-feature codes to a degree that allows integrating them with sufficiently activated stimulus-feature codes. If so, some degree of S-R integration may take place even if the

planned action is eventually not carried out—as is the case in a no-go trial.

#### Method

Sixteen adults participated; they all fulfilled the same criteria as applied in Experiment 1. The method was as in Experiment 1, with the following exceptions. Participants prepared the R1 as signaled by the response cue and performed it in response to a 50-ms trigger tone. As in Experiment 3, the tone always appeared 1,000 ms after response cue offset and 1,000 ms before S2 onset. However, the tone varied in frequency: A low tone (200 Hz) signaled a go trial, in which participants were to carry out R1 as precued, whereas a high tone (800 Hz) signaled a no-go trial, in which R1 was to be withheld. The probability of a go signal was 50%. The go/no-go manipulation affected only the R1-related task; the S2-R2 task was exactly as in Experiments 1 through 3. Each session was composed of five 64-trial blocks, the first serving as a practice block. Each block was composed by a factorial combination of the two shapes (*O* vs. *X*) and two locations (top vs. bottom) of S2; the repetition versus alternation of shape, location, and response; and (previous) trial type (go vs. no go).

#### Results

R1 was carried out in 213 ms, on average; errors were rare (0.6%), as were anticipations (0.03%) and response omissions or false alarms in no-go trials (2.5%). After excluding anticipations (0.9%) and omissions (0.1%), R2 data were analyzed as a function of shape and location repetition, response repetition, and previous trial type (go vs. no go; see Table 4).

The RT analysis yielded a main effect of shape repetition,  $F(1, 15) = 6.61$ ,  $MSE = 2,472$ ,  $p < .05$ , that was modified by trial type,  $F(1, 15) = 17.61$ ,  $MSE = 894$ ,  $p < .001$ . Whereas the repetition of stimulus shape produced a 32-ms priming effect after go trials, no priming effect (0 ms) was obtained following no-go trials. Trial type also interacted with location repetition,  $F(1, 15) = 6.80$ ,  $MSE = 884$ ,  $p < .05$ , reflecting that the 10-ms advantage for location repetitions observed after go trials turned into a 10-ms disadvantage after no-go trials. More important, the remaining effects were as expected: a not-quite-significant interaction of shape repetition and location repetition,  $F(1, 15) = 3.91$ ,  $MSE = 1,894$ ,  $p < .07$ , and reliable interactions of response repetition with

Table 4  
Means of Mean Reaction Times for Responses to Stimulus 2 ( $RT_{R2}$ ; in Milliseconds) and Percentages of Errors on Response 2 ( $PE_{R2}$ ) in Experiment 4

Match	Go				No go			
	$RT_{R2}$		$PE_{R2}$		$RT_{R2}$		$PE_{R2}$	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Neither	501	118	1.1	3.1	496	123	0.0	0.0
Shape (S)	507	136	3.9	4.5	529	130	2.4	5.3
Location (L)	513	115	2.1	4.0	531	128	2.5	4.4
Response (R)	539	129	5.6	5.3	532	151	3.4	5.6
SL	497	123	6.1	8.6	533	167	3.9	4.8
SR	501	122	2.4	4.8	509	126	1.0	3.9
LR	540	136	3.6	4.4	528	131	4.4	6.5
SLR	460	124	0.7	2.0	514	150	1.5	2.6

Note. Values shown are as a function of go versus no-go trials (Stimulus 1 → Response 1) and the feature match between the shape and location of Stimulus 1 and Stimulus 2 and the match between Response 1 and Response 2.



shape repetition,  $F(1, 15) = 15.91$ ,  $MSE = 2,038$ ,  $p < .001$ , and location repetition,  $F(1, 15) = 7.68$ ,  $MSE = 853$ ,  $p < .05$  (see Figure 6). There was no evidence that these effects were modified by trial type ( $ps > .21$ ). Separate ANOVAs revealed that a Shape  $\times$  Response interaction was reliable for both go and no-go trials ( $ps < .05$ ), whereas the Location  $\times$  Response interaction was significant for no-go trials ( $p < .05$ ) but not go trials ( $p = .20$ ), and the Shape  $\times$  Location interaction was significant for go trials ( $p < .05$ ) but not no-go trials ( $p = .50$ ).

The error analysis revealed a reliable interaction of Shape Repetition  $\times$  Response repetition,  $F(1, 15) = 14.55$ ,  $MSE = 27.88$ ,  $p < .005$ , and close-to-significant interaction of location repetition and response repetition,  $F(1, 15) = 3.82$ ,  $MSE = 15.37$ ,  $p < .07$ ; both effects followed the same pattern as the RTs. The only effect involving trial type was a not-quite-reliable three-way interaction, with shape repetition and response repetition,  $F(1, 15) = 4.29$ ,  $MSE = 6.99$ ,  $p < .06$ , indicating a somewhat less pronounced interaction of shape and response after no-go trials. However, separate analyses confirmed that the interaction was reliable for both go and no-go trials ( $ps < .05$ ). The separate analyses also revealed a reliable interaction of location and response in go trials ( $p < .05$ ) but not no-go trials ( $F < 1$ ). In view of the opposite pattern in the RTs, where the effect was more reliable in no-go trials, this suggests a speed-accuracy trade-off.

### Discussion

Turning the simple RT part of Experiments 1 through 3 into a go/no-go task did not eliminate S-R integration. In fact, an ANOVA including the RT data from post-go trials and averages from the two SOA = 0 conditions of Experiment 3 provided no evidence for any reduction of the size of integration effects ( $ps > .48$ ). Another interesting outcome is that post-no-go trials produced somewhat smaller but still reliable integration effects as well, which supports the idea that planning an action may be sufficient for binding its features to accompanying stimulus events. Apart from these, for present purposes, it is interesting to note that no-go trials eliminated the otherwise reliable priming effects for

stimulus shape and location. This suggests that withholding a response in the presence of a stimulus leads to some sort of marking or suppression of the codes representing that stimulus, a particular variant of negative priming (Tipper, 1985). I come back to this issue in the General Discussion section.

### Experiment 5

Experiment 4 provided no evidence that S1-R1 integration is affected by decreasing the attentional resources available for processing the irrelevant S1 through requiring participants to identify, rather than detect, the R1 trigger tone. Although this may be taken to suggest that S-R integration is an automatic process (however defined), such a conclusion is difficult to defend against the possible objection that processing the tone was still not sufficiently demanding—especially in the absence of any agreed-upon criterion for how “sufficient” might be defined. In an attempt to further increase the demands on tone processing, I therefore replicated Experiment 4 with go and no-go tones that are more difficult to discriminate.

### Method

Eight adults participated; they all fulfilled the same criteria as applied in Experiment 1. The method was as in Experiment 4, except that the two tones were less discriminable (470 vs. 530 Hz).

### Results

R1 was carried out in 247 ms, on average; errors were rare (0.7%), anticipations were absent, and response omissions or false alarms in no-go trials were infrequent (3.7%). After excluding anticipations (1.9%) and response omissions (0.4%), R2 data were analyzed analogously to Experiment 4 (see Table 5).

The RTs showed a main effect of shape repetition,  $F(1, 7) = 6.20$ ,  $MSE = 2,322$ ,  $p < .05$ , that was modified by trial type,  $F(1, 7) = 11.45$ ,  $MSE = 676$ ,  $p < .05$ , again indicating that repeating shape produced a reliable priming effect after go trials (37 ms) but not after no-go trials (6 ms, *ns*). Response interacted with shape repetition,  $F(1, 7) = 5.90$ ,  $MSE = 2,575$ ,  $p < .05$ , and with location repetition,  $F(1, 7) = 18.53$ ,  $MSE = 466$ ,  $p < .005$ . Of importance, the former effect was further modified by trial type,  $F(1, 7) = 6.29$ ,  $MSE = 625$ ,  $p < .05$ . As shown in Figure 7 and confirmed by separate analyses, the interaction between shape and response was reliable after go trials ( $p < .05$ ) but not after no-go trials ( $p = .30$ ).

The only reliable effects in the error rates were the interactions of response repetition with shape repetition,  $F(1, 7) = 17.45$ ,  $MSE = 11.36$ ,  $p < .005$ , and location repetition,  $F(1, 7) = 6.20$ ,  $MSE = 15.87$ ,  $p < .05$ , which followed the same pattern as the RTs. Separate ANOVAs showed a somewhat different picture, which, however, matched the RTs even more closely: All three interactions were reliable for go trials ( $ps < .05$ ) but not for no-go trials ( $ps > .15$ ).

### Discussion

As the elevated RTs for R1 suggest, processing the trigger tone was more difficult than in Experiment 4, and yet S1 and R1 features were still integrated. Again, even the effect sizes were comparable, as suggested by an ANOVA across Experiments 4

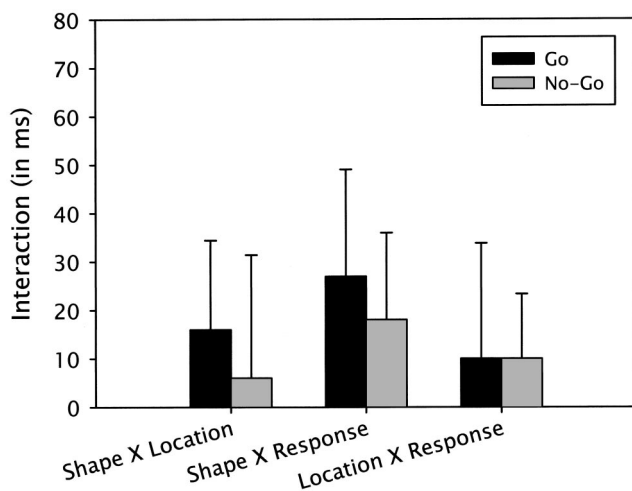


Figure 6. Sizes of two-way interaction effects in the reaction times in Experiment 4 as a function of go versus no-go trials. Error bars indicate confidence intervals for the corresponding interaction effects.

Table 5  
Means of Mean Reaction Times for Responses to Stimulus 2 ( $RT_{R2}$ ; in Milliseconds) and Percentages of Errors on Response 2 ( $PE_{R2}$ ) in Experiment 5

Match	Go				No go			
	$RT_{R2}$		$PE_{R2}$		$RT_{R2}$		$PE_{R2}$	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Neither	504	74	0.0	0.0	510	92	0.0	0.0
Shape (S)	503	106	0.7	2.1	510	84	2.1	4.2
Location (L)	521	120	0.7	2.1	523	77	1.5	2.7
Response (R)	551	111	7.0	4.6	534	118	3.6	4.2
SL	513	106	5.5	6.4	533	92	3.0	8.4
SR	496	101	2.1	4.2	528	120	0.7	2.1
LR	547	125	2.9	3.1	530	94	2.2	3.0
SLR	462	125	0.0	0.0	503	126	2.1	4.2

Note. Values shown are as a function of go versus no-go trials (Stimulus 1 → Response 1) and the feature match between the shape and location of Stimulus 1 and Stimulus 2 and the match between Response 1 and Response 2.

and 5, in which the experiment factor did not modify any integration effect ( $ps > .23$ ). Thus, there is still no evidence that blocking S1 from attentional resources affects its integration with R1. However, Experiment 5 provides even clearer evidence than Experiment 4 that actually performing an action does make a difference for integration. Although withholding an action does not prevent integration, carrying it out strongly boosts the strength of the binding between shape, the relevant S2 feature, and the response.

### Experiment 6

This experiment was a further attempt to increase the attentional demands on tone processing, so as to further reduce the capacity available for the processing of S1. Instead of cuing R1 in advance and of using two tones as go and no-go signals, R1 was now signaled by the frequency of the tone (i.e., at the time S1 was presented). Accordingly, S1 appeared at a point in time when participants were not only to decide whether or not to carry out the

prepared response but when they were to identify the tone and to select the appropriate response. Unsurprisingly, this led to a further, massive elevation of the time to carry out R1, which suggests that the attentional demands of the tone-related task were further increased.

### Method

Sixteen adults participated; they all fulfilled the same criteria as applied in Experiment 1. The method was as in Experiment 5, with the following exceptions. Most important, participants were not presented with an R1 precue and were thus unable to prepare the first response in advance. Instead, they awaited the tone and responded to its pitch: For half of the participants low pitch (470 Hz) signaled a left-hand keypress and high pitch (530 Hz) a right-hand keypress, whereas the other half received the opposite tone–key mapping. In other words, participants carried out a speeded binary-choice response to the tone (R1) followed by a speeded binary-choice response to the visual S2 (R2). The visual S1 always accompanied the tone, that is, the SOA between response trigger and S1 was 0 ms and the SOA between trigger or S1 and S2 was 1,000 ms. There were no no-go trials. The only other modification was that responses were made on the computer keyboard, using the left and right shift key. Each session was composed of seven 32-trial blocks, the first serving as a practice block. Each block was composed by a factorial combination of the two shapes (*O* vs. *X*) and two locations (top vs. bottom) of S2, and the repetition versus alternation of shape, location, and response.

### Results

R1 was carried out in 522 ms, on average; errors occurred in 4.5% of the trials, omissions in 1.5%, and anticipations were not observed. After excluding anticipations (2.9%) and response omissions (0.1%), R2 data were analyzed as a function of shape and location repetition and response repetition (see Table 6).

In the RTs, response repetition produced a main effect,  $F(1, 15) = 7.86, MSE = 2,030, p < .05$ , and it interacted with shape repetition,  $F(1, 15) = 54.36, MSE = 2,052, p < .001$ , and location repetition,  $F(1, 15) = 10.23, MSE = 1,187, p < .01$ ; see Figure 8 for an overview.

The error rates revealed main effects of shape repetition,  $F(1, 15) = 7.89, MSE = 18.91, p < .05$ , and response repetition,  $F(1,$

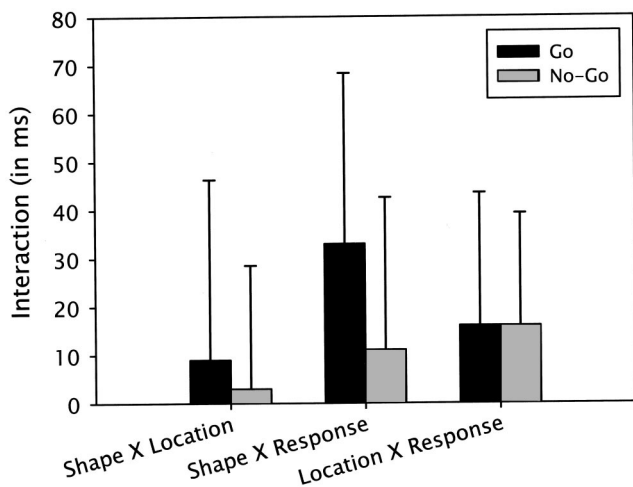


Figure 7. Sizes of two-way interaction effects in the reaction times in Experiment 5 as a function of go versus no-go trials. Error bars indicate confidence intervals for the corresponding interaction effects.

15) = 7.93,  $MSE = 115.81$ ,  $p < .05$ . Shape repetition interacted with location repetition,  $F(1, 15) = 5.84$ ,  $MSE = 18.43$ ,  $p < .05$ , and response repetition interacted with both shape repetition,  $F(1, 15) = 63.44$ ,  $MSE = 29.19$ ,  $p < .001$ , and location repetition,  $F(1, 15) = 11.08$ ,  $MSE = 64.40$ ,  $p < .005$ . Whereas the two latter effects followed the standard RT pattern, the Shape  $\times$  Location interaction did not: For shape repetitions, repeating stimulus location was less advantageous than location alternation (8.7% vs. 6.3%), whereas the opposite was true for shape alternations (9.0% vs. 10.2%).

*Discussion*

The results are clear cut. There was no indication that presenting the visual S1 during a now full-fledged binary RT task signaled by a tone would hamper S1-R1 integration. If anything, the Shape  $\times$  Response interaction was increased—in fact, it was numerically the largest effect of the whole study, even if the increase compared with that in Experiment 5 was not quite significant ( $p < .07$ ). Hence, again, there was no reliable indication of a dependency of S-R integration on attentional capacity.

Experiment 7

Experiment 7 was motivated by finding such a strong effect of shape–response integration in Experiment 6. On the one hand, the numerical increase compared with that in Experiment 5 was not reliable, and it is unclear whether the effect can be replicated at this size. On the other hand, however, there is another possibility of more theoretical interest, which Experiment 7 was aimed to evaluate. If we assume that processing S1 takes some time and that the activation of S1-related feature codes outlives S1’s appearance, the processes with which this activation coexisted in time were rather different in Experiments 5 and 6. In Experiment 5, as in the other experiments of this study, S1 appeared at a time when planning of R1 was most likely completed, and the plan was merely maintained until execution. In contrast, in Experiment 6, planning of R1 only began when S1 appeared, so that the activation of S1 codes largely overlapped with the action-planning process. It may be that this strengthened the links between S1 and the representation of R1. Experiment 7 evaluated this possibility by comparing integra-

Table 6  
Means of Mean Reaction Times for Responses to Stimulus 2 ( $RT_{R2}$ ; in Milliseconds) and Percentages of Errors on Response 2 ( $PE_{R2}$ ) in Experiment 6

Match	$RT_{R2}$		$PE_{R2}$	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Neither	494	76	1.7	2.5
Shape (S)	548	80	4.7	5.0
Location (L)	521	43	4.5	4.3
Response (R)	586	86	18.8	11.6
SL	583	68	12.5	7.7
SR	540	80	7.8	10.6
LR	592	89	13.4	8.5
SLR	518	71	4.8	7.0

Note. Values shown are as a function of the feature match between the shape and location of Stimulus 1 and Stimulus 2 and the match between Response 1 and Response 2.

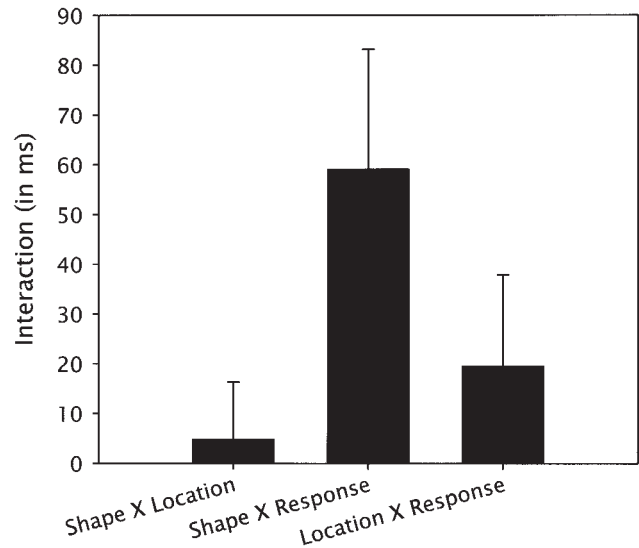


Figure 8. Sizes of two-way interaction effects in the reaction times in Experiment 6. Error bars indicate confidence intervals for the corresponding interaction effects.

tion effects under two conditions. In both conditions R1 was precued—by the same two tones used in Experiment 6—and later triggered by a third, neutral tone. However, S1 either appeared together with the trigger tone (go signal condition), a rather standard condition that was intended to replicate the previous findings, or it appeared together with the R1 precue (R1 cue condition). This latter condition should maximize the overlap of S1 activation and the R1 planning process. If this overlap increases S1-R1 integration, stronger effects, at least a stronger Shape  $\times$  Response interaction, would be expected in the R1 cue condition than in the go signal condition.

*Method*

Seventeen adults participated; they all fulfilled the same criteria as applied in Experiment 1. The method was as in Experiment 6, with the following exceptions. First, R1 was again precued. The same two tones that in Experiment 6 signaled R1 were now used as precues: A 470-Hz tone indicated a left-hand keypress, and a 530-Hz tone a right-hand keypress in half of the participants, while the other half received the opposite tone–key mapping. The cued responses were to be prepared but to be withheld until presentation of a 50-ms, 200-Hz trigger tone that always appeared 2,000 ms after the R1 cue. S2 appeared another 1,000 ms later, so that the SOA between R1 trigger and S2 was again 1 s. The second modification was that the visual S1 could either accompany the R1 trigger tone, analogously to Experiment 5, or accompany the R1 cue tone. In summary, the 2-s intertrial interval was followed by a 50-Hz R1 cue (and, in the R1 cue condition, S1); 2,000 ms later the R1 trigger appeared (and, in the go signal condition, S1), followed by S2 1,000 ms later. Participants served in single sessions. Each session was composed of six 64-trial blocks, the first serving as a practice block. Each block was composed by a factorial combination of the two shapes (*O* vs. *X*) and two locations (top vs. bottom) of S2; the repetition versus alternation of shape, location, and response; and the time point of S1 presentation (early vs. late).

*Results*

R1 was carried out in 487 ms on average, errors occurred in 3.4% of the trials, anticipations in .7% and response omissions in

.9% of the trials. After excluding anticipations (.8%) and response omissions (1.0%), R2 data were analyzed as a function of shape and location repetition, response repetition, and the time point of S1 presentation (see Table 7).

The RTs yielded a main effect of time point,  $F(1, 16) = 15.04$ ,  $MSE = 53,998$ ,  $p < .001$ , and reliable interaction of Shape  $\times$  Location Repetition,  $F(1, 16) = 5.19$ ,  $MSE = 657$ ,  $p < .05$ . The interaction of Shape  $\times$  Response Repetition,  $F(1, 16) = 9.39$ ,  $MSE = 1,247$ ,  $p < .01$ , was modified by time point,  $F(1, 16) = 10.31$ ,  $MSE = 1,657$ ,  $p < .005$ , indicating that it was reliable only after S1 accompanied the go signal; see Figure 9. Likewise, the interaction of Location  $\times$  Response Repetition,  $F(1, 16) = 7.38$ ,  $MSE = 827$ ,  $p < .05$ , depended on time point,  $F(1, 16) = 11.55$ ,  $MSE = 9,722$ ,  $p < .005$ , that is, only occurred after S1 appeared together with the go signal.

The error rates exhibited main effects of time point,  $F(1, 16) = 6.14$ ,  $MSE = 57.27$ ,  $p < .05$ ; location repetition,  $F(1, 16) = 5.74$ ,  $MSE = 7.45$ ,  $p < .05$ ; and response repetition,  $F(1, 16) = 15.60$ ,  $MSE = 14.90$ ,  $p < .001$ , the latter modified by time point,  $F(1, 16) = 9.83$ ,  $MSE = 19.45$ ,  $p < .01$ . Fewer errors were made with the early than the late time point of S1 (2.6% vs. 4.9%), and more errors were made with location repetition than alternation (4.2% vs. 3.4%). After an early presentation of S1, response repetitions yielded about the same performance as alternations (2.7% vs. 2.5%), but after a late presentation, repetitions were associated with considerably more errors than alternations (6.7% vs. 3.1%). Time point also affected the shape repetition effect,  $F(1, 16) = 7.74$ ,  $MSE = 13.49$ ,  $p < .05$ , so that shape repetitions and alternations yielded comparable error rates after an early presentation of S1 (3.0% vs. 2.3%) but a repetition benefit after a late presentation (4.0% vs. 5.8%).

More important, response interacted with shape repetition,  $F(1, 16) = 19.42$ ,  $MSE = 28.07$ ,  $p < .001$ , and with Location Repetition  $\times$  Response Repetition,  $F(1, 16) = 6.66$ ,  $MSE = 19.17$ ,  $p < .05$ , and both effects were further modified by time point,  $F(1, 16) = 11.85$ ,  $MSE = 27.51$ ,  $p < .005$ , and  $F(1, 16) = 5.04$ ,  $MSE = 15.85$ ,  $p < .05$ . Separate analyses revealed that the two-way interactions were reliable only after a late but not after an early S1 presentation, the former following the standard RT pattern. Time point was involved in another three-way interaction with shape and

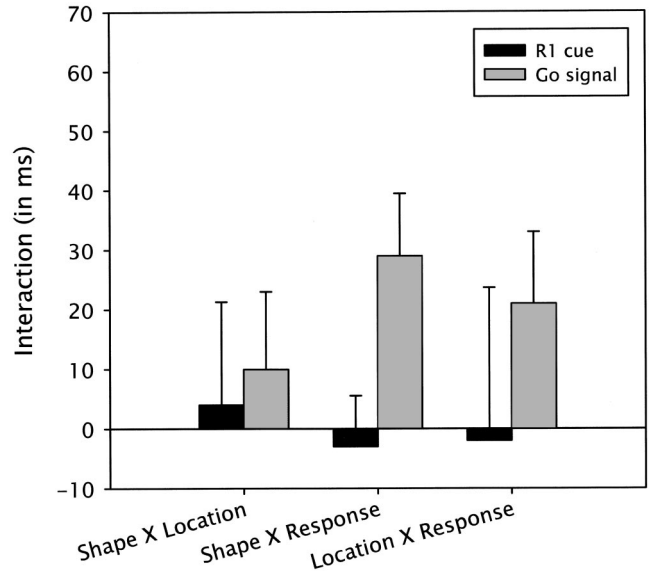


Figure 9. Sizes of two-way interaction effects in the reaction times in Experiment 7 as a function of the time point of Stimulus 1 presentation. Error bars indicate confidence intervals for the corresponding interaction effects. R1 = Response 1.

location repetition,  $F(1, 16) = 5.25$ ,  $MSE = 19.37$ ,  $p < .05$ . However, the underlying pattern was difficult to interpret, as the Shape  $\times$  Location interaction did not reach significance for either time point when analyzed separately.

Discussion

S1 was integrated with R1 if it appeared close to the execution or the eventual abandonment of the response (in go or no-go trials of the go signal condition, respectively) but not if S1 appeared during or close to the planning of R1 (i.e., in the R1 cue condition). This outcome does not support the planning-overlap hypothesis but, rather, suggests that S-R integration does not take place while and in the process of creating and consolidating the action plan. A

Table 7  
Means of Mean Reaction Times for Responses to Stimulus 2 ( $RT_{R2}$ ; in Milliseconds) and Percentages of Errors on Response 2 ( $PE_{R2}$ ) in Experiment 7

Match	Response 1 cue				Go signal			
	$RT_{R2}$		$PE_{R2}$		$RT_{R2}$		$PE_{R2}$	
	M	SD	M	SD	M	SD	M	SD
Neither	429	97	0.8	2.4	503	87	0.3	1.2
Shape (S)	439	94	3.9	5.3	539	102	2.0	5.0
Location (L)	437	99	3.0	6.0	540	75	2.7	3.3
Response (R)	423	99	2.5	3.8	566	105	11.0	8.8
SL	430	91	2.5	3.5	555	99	7.5	7.6
SR	430	106	3.1	6.8	543	90	3.2	4.2
LR	427	100	2.9	4.8	559	95	9.1	8.2
SLR	434	93	2.3	3.3	517	78	3.3	3.5

Note. Values shown are as a function of time of Stimulus 1 presentation and the feature match between the shape and location of Stimulus 1 and Stimulus 2 and the match between Response 1 and Response 2.

possible alternative, which I develop in the General Discussion section, is that actions get integrated with the present (or most recent) stimulus context no earlier than when the success of the action (or its omission) is evaluated. At that time the codes of (task-irrelevant) stimuli that appeared as early as the original response cue (i.e., S1 in the R1 cue conditions) may be no longer activated to a degree that is necessary to pass the integration threshold (Hommel, 2004).

### Experiment 8

Experiments 4 through 7 followed the strategy to reduce the attentional capacity available for S1 by requiring participants to attend to another sensory dimension. Experiment 8 aimed at the same goal by following an alternative strategy: This time, R1 was signaled by a visual stimulus different from and appearing at a different location than the visual S1, which was thought to create direct competition for attentional resources between the R1 trigger and S1. That is, participants carried out two visuo-manual binary choice tasks in a row, a left or right keypress to the letters *I* or *T* followed by a left or right keypress to the letters *O* or *X*, while S1 (an *O* or *X*) appeared as an irrelevant flanker accompanying the first target.

### Method

Sixteen adults participated; they all fulfilled the same criteria as applied in Experiment 1. The method was as in Experiment 6, with the following exceptions. As in Experiment 6, participants were not presented with an R1 precue and did not prepare the first response in advance. Instead, they awaited a visual letter and responded to its shape: For half of the participants the uppercase letter *I* signaled a left-hand keypress and a *T* a right-hand keypress, whereas the other half received the opposite letter-key mapping. The R1 trigger letter was always white and always appeared for 280 ms in the central box. It was accompanied (SOA = 0 ms) by the visual S1 (an *O* or *X* in the top or bottom box), which was always green. Participants were instructed to focus on the white letter and ignore the green stimulus. One thousand milliseconds after the onset of the R1 trigger and S1, S2 appeared to signal R2. As in all previous experiments, S2 was an *O* or *X* in the top or bottom box, with one letter signaling a left-hand keypress and the other a right-hand keypress. The only modification to S2 was that S2 was presented in green, so that it always matched S1 in color. The only other modification to the method was that responses were made on the external keyboard used in Experiments 1 through 5. Each session was composed of seven 32-trial blocks, the first serving as a practice block. Each block was composed by a factorial combination of the two shapes (*O* vs. *X*) and two locations (top vs. bottom) of S2 and the repetition versus alternation of shape, location, and response.

### Results

R1 was carried out in 506 ms, on average; errors, anticipations, and response omissions accounted for 3.4%, 0%, and 1% of the trials, respectively. After excluding anticipations (1.5%) and response omissions (0.03%), R2 data were analyzed as a function of shape and location repetition and response repetition (see Table 8).

RTs revealed an interaction between shape repetition and location repetition,  $F(1, 15) = 5.76$ ,  $MSE = 548$ ,  $p < .05$ , and interactions of response repetition with shape repetition,  $F(1, 15) = 13.94$ ,  $MSE = 1,523$ ,  $p < .005$ , and location repetition,  $F(1, 15) = 5.06$ ,  $MSE = 852$ ,  $p < .05$ ; Figure 10 provides an overview.

Table 8

*Means of Mean Reaction Times for Responses to Stimulus 2 ( $RT_{R2}$ ; in Milliseconds) and Percentages of Errors on Response 2 ( $PE_{R2}$ ) in Experiment 8*

Match	$RT_{R2}$		$PE_{R2}$	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Neither	503	85	1.9	4.0
Shape (S)	531	95	4.3	4.5
Location (L)	529	93	1.9	3.7
Response (R)	547	101	12.2	9.8
SL	538	92	6.2	4.2
SR	524	106	10.2	7.9
LR	551	84	10.3	7.2
SLR	507	106	7.4	4.9

*Note.* Values shown are as a function of the feature match between the shape and location of Stimulus 1 and Stimulus 2 and the match between Response 1 and Response 2.

The error rates did not yield any reliable effect, but the interactions between response and shape repetition and between response and location repetition approached the significance level ( $p < .06$  and  $p < .08$ , respectively). Their pattern followed the RTs.

### Discussion

S1 and R1 features were integrated even in the face of a competing visual target stimulus. An ANOVA on the RTs from Experiments 4, 5, and 8 revealed that none of the three interactions were modified by experiment ( $p > .70$ ). In another ANOVA on the RTs from Experiments 6 and 8, two of the three interactions were also unaffected ( $p > .30$ ); only the Shape  $\times$  Response interaction was larger in Experiment 6,  $F(1, 30) = 9.92$ ,  $MSE = 1,787$ ,  $p < .005$ . Thus, there is again little evidence that S-R integration is sensitive to the lack of attentional capacity.

### General Discussion

The aim of this study was to explore how much attention the creation of S-R bindings requires, and the answer seems somewhat complex but clear. As pointed out in the introduction, one can already rule out that the code of any stimulus that is present when a response is carried out is lumped together with response-related codes. This assumption would be at odds with the observation that it is mainly features that are somehow related to the task that are considered for integration. Task relevance is apparently loosely defined in the context of feature integration: A feature may gain this status by being defined on a dimension that signals another response in the same task (Hommel, 1998) or by being related to the dimension on which the responses are defined (Hommel, in press). It may even be that features are considered if they are sufficiently salient in the present context or helpful to discriminate targets from other stimuli (Hommel, 2004; Hommel & Colzato, 2004). Whatever the precise conditions may be, it is clear that not all features become integrated and that the likelihood of being integrated varies with the role the dimension of a given feature plays in the particular task (Hommel, 2004). This suggests that task-relevant feature dimensions are "intentionally weighted" (Hommel, Müsseler, Aschersleben, & Prinz, 2001), that is, are

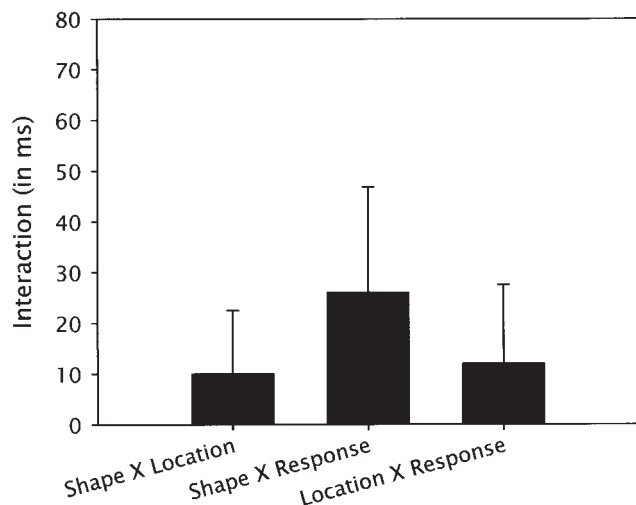


Figure 10. Sizes of two-way interaction effects in the reaction times in Experiment 8. Error bars indicate confidence intervals for the corresponding interaction effects.

primed in a way that enhances the activation of codes of features defined on these dimensions—enhanced to a degree that increases their chances of becoming integrated.

As another caveat, the failure to find evidence for a reliable impact of attention on feature integration should not be taken as direct proof that integration is independent of attention. One reason for this is that the concept of intentional weighting is not identical with but can be translated into the contingent-capture account of Folk, Remington, and Johnston (1992). Folk et al. assumed that task-relevant perceptual dimensions are included in an attentional set that determines which stimuli attract attention in a (then) automatic fashion—a kind of prepared reflex (Hommel, 2000). If we add the assumptions that (a) even response dimensions can be considered in attentional sets and that (b) attentional sets are so inert that they cannot be, or at least are not, switched between processing S1 and S2, one can argue that S1 attracts at least some degree of “contingent attention” by virtue of the fact that it matches the set actually implemented for S2. Another reason to be cautious about the role of attention in feature integration is that the present conclusions rest upon acceptance of the null hypothesis. Even though the attentional manipulations used in this study did not modify the sizes of the integration measures, we cannot exclude the possibility that more drastic manipulations would be more successful. All stimuli used here as S1 were clearly visible and presented with an abrupt onset, conditions that are known to attract exogenous attention. Reducing the abruptness and decreasing the visibility of the stimuli, or even presenting them under subliminal conditions, may be more efficient to work against integration. Likewise, using more drastic manipulations to exhaust the attentional capacity of participants, such as presenting the trigger tones under extremely unfavorable signal-to-noise conditions, may have a reliable effect.

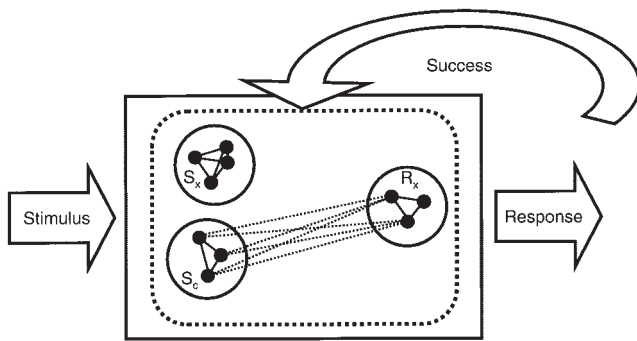
On the other hand, however, the present findings do suggest that, to get its task-related features bound to a response, a stimulus does not have to be necessary or useful for the task at hand or be reacted upon (Experiments 2–8), does not have to precede the response in time (Experiments 2–3), and may even compete with

a target stimulus that signals a response (Experiments 6 and 8), and the response does not even have to be carried out (Experiments 4–5). Only one condition seems to be important: Although the exact temporal relation between the to-be-integrated stimulus and the response apparently does not matter (Experiment 3), the stimulus has to appear at least close to the eventual execution or abandonment of the response (Experiment 7).

This latter observation is particularly important, as it implies a temporal dissociation between the integration of action features (i.e., planning an action) and the integration of stimulus and response features. Logically, both processes may fall together or could at least take place in parallel: One integrational act may create the whole transient network by binding all action features together and some or all of them to currently (sufficiently) activated codes of stimulus features. If so, one would have expected similar outcomes in the two temporal presentation conditions of Experiment 7, that is, considerable binding even if S1 appears early in R1 planning. However, as the findings show, temporal proximity between a context stimulus and the planning process does not guarantee that this stimulus is bound to the planned action. Accordingly, if one assumes that action planning involves the binding of action-related features—an assumption that is well supported by independent evidence (Müsseler & Hommel, 1997; Stoet & Hommel, 1999; Wühr & Müsseler, 2001)—one needs to conjecture that S-R binding takes place later in time than and, apparently, independent of the process subserving integration in action planning. This conclusion fits with the recent observations of Colzato and colleagues (2004, 2005) that drugs impacting the muscarinic-cholinergic system affect the binding of stimulus features to other stimulus features (shape–location and shape–color binding) but not to response features. Under the assumption that binding in the visual cortex is driven by the cholinergic system (Munk, 2003; Rodriguez, Kallenbach, Singer, & Munk, 2000; Rodriguez, Kallenbach, Singer, & Munk, 2004), the impact on shape–location and shape–color binding is to be expected.<sup>3</sup> However, if at the same time S-R binding is unaffected, this means either that the mechanism creating these bindings is driven by another arousal system or that it operates in a way that is less sensitive to fluctuations in cholinergic energy supply (Colzato et al., 2005). Either way, these observations suggest that the mechanisms underlying local feature integration (in visual or premotor areas) are not identical and are probably not strongly related to global feature integration covering long cortical distances—a conclusion that is also suggested by magnetoencephalographic studies of intercortical interactions (Gross et al., 2004) and neural-network simulations (Kopell, Ermentrout, Whittington, & Traub, 2000).

Figure 11 captures some of the theoretical implications of these considerations. Facing a particular stimulus, say,  $S_x$ , can be assumed to activate the codes of its features, four in the example. The degree of activation depends on the task relevance of the particular dimension and, perhaps, on some more, not yet fully

<sup>3</sup> This stronger reliance of purely visual bindings on arousal factors may also explain why the respective interactions (here between shape and location) are often much smaller or less reliable than effects indicating S-R bindings. A more systematic control and manipulation of arousal-related factors (especially those with an impact on the muscarinic-cholinergic system, such as caffeine and alcohol) may help to get a better handle on these effects in the future.



*Figure 11.* Sketch of a multiple-integration model of event-file creation. Target stimuli (here:  $S_x$ ) and directly or indirectly task-related context stimuli (here:  $S_c$ ) are coded by activating the codes of their features (to the degree that the particular feature is related to the task or salient for other reasons); these codes will be bound into coherent object representations, which link feature codes belonging to the same object (see straight lines). Likewise, action plans (here: of response  $R_x$ ) are created by activating and binding the codes of response-relevant features. If an action is rewarded, a global integration process is triggered (see dotted box) that binds codes of relevant response features to sufficiently activated stimulus-feature codes (see dotted links; not all are shown).

explored characteristics, such as the contextual salience of a feature. Activation is followed by local feature integration, that is, by a process that interconnects the coactivated features,<sup>4</sup> provided that their activation passes a particular, perhaps modifiable integration threshold (Hommel, 2004). Local binding creates object representations, symbolized in Figure 11 by circles. In view of the present findings, it is necessary to assume that more than one object representation can be maintained at a time (whether such representations can also be created in parallel the present data cannot tell), an assumption that is consistent with findings from visual delayed-matching tasks (Luck & Vogel, 1997). Accordingly,  $S_x$  does not have to be the only object to be coded and integrated; an irrelevant context stimulus, say,  $S_c$ , can also be represented concurrently—if it only enjoys sufficient “intentional weighting.” Planning an action, say,  $R_x$ , is assumed to follow the same logic, only the feature codes are not directly activated by a stimulus. Rather, they may be specified by some internal goal representation and/or indirectly activated via an S-R rule. Activating the codes of the appropriate action features is followed by binding them to an integrated action plan (Stoet & Hommel, 1999), again indicated by a circle.

In the cartoon model, stimulus and response integration are independent mechanisms, certainly independent in timing and perhaps independent in terms of the underlying neural process. And yet, the codes that get integrated stem from the same pool (Hommel et al., 2001; Prinz, 1990). That is, the very same code that is bound to a particular object representation, for example, a code of the object’s shape or relative location, may on another occasion be bound to an action plan to specify the parameters of a grasp or reach, respectively. Accordingly, if a stimulus and a response share a particular feature, such as being located to the left of some reference point, their representations are directly interlinked via the code representing that feature. This characteristic accounts for S-R compatibility (Hommel, 1997) and code-occupation effects (Müsseler & Hommel, 1997; Stoet & Hommel, 1999).

More important in the present context, however, are transient bindings. The model assumes that response decisions that result in success—whether signaled by the presence of a reward or the absence of an error signal, or cognitively inferred—lead to the binding of the codes that were (sufficiently) active around the time this success was achieved (see the dotted links in Figure 11; Schultz, 2004). It is tempting to consider this kind of success-induced binding as the initial stage of operant conditioning, and yet surprisingly little is known about the relation and possible transition between feature integration and long-term learning. Worse, some of the few findings that speak to that issue do not suggest a strong and direct connection (Colzato, Raffone, & Hommel, in press). At any rate, in contrast to predictions from standard learning theories (e.g., Logan, 1988; Rescorla & Wagner, 1972; Thorndike, 1932), it is necessary to assume that the representation of the most recent episode—the newest event file, that is—has a greater impact on current behavior than all previous encounters with the respective stimulus or response. This follows from the design used to demonstrate the existence of event files, such as in the present study: On average, each combination of S1 features and/or R1 alternatives is as probable (and as frequent) as any other, so that purely frequency-based learning theories have no reason to predict trial-to-trial effects of the sort investigated here. This means that, whether an event file represents the first step toward a long-term memory entry or not, it affects action control to a degree that goes beyond, and therefore cannot be explained by, its possible contribution to S-R learning.

Success-based integration is thus claimed to create a kind of episodic snapshot that does not distinguish between formally relevant and irrelevant events, and that it is during this process that the features of S1 get “glued” to features of R1. As the integration process is triggered at some point after the action has been carried out (or abandoned, as in no-go trials), it is easy to see why context stimuli get bound even if they appear briefly after the actual target stimulus (Experiments 2–3) but not if they are presented a few seconds before the response trigger (Experiment 7). Success-based integration should not be restricted to go trials but also integrate active components on no-go trials. However, as has been shown in this article, the main effects of shape and, in one case, location repetitions are strongly reduced after no-go trials, suggesting that withholding a response goes along with suppressing the currently activated stimulus feature codes (cf. Houghton & Tipper, 1994). If so, chances are that stimulus feature codes no longer reach the threshold for integration at the time this integration eventually takes place—which explains why binding effects were present but small after no-go trials.

In summary, it seems that not much is needed to create an event file. Features of stimuli and responses are integrated whenever the dimensions they are defined on are somehow related to the task,

<sup>4</sup> Actually, the rules underlying this interconnection are more complex than Figure 11 suggests. This is obvious from two observations: (a) Bindings seem to be binary, as suggested by the fact that the interactions pointing to them are commonly of no higher order than two-way (cf. Hommel, 1998, 2004), and (b) binary bindings are apparently not transitive, that is, reliable interactions between features  $x$  and  $y$  and between  $x$  and  $z$  are often not accompanied by interactions between  $y$  and  $z$  (Hommel, 1998; Hommel & Colzato, 2004). This means that even local (e.g., visual) bindings do not seem to enter a single superstructure but, instead, seem to create a multilayered associative network (Hommel, 1998).

but they do not seem to require explicit attention or functional significance to get involved in S-R bindings. Even though local bindings of stimulus-feature codes and of action-feature codes seem to operate in the same representational domain and on the same codes as cross-domain S-R bindings, the latter are apparently created at a different point in time than the former and, presumably, are mediated by different neural mechanisms.

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