

Visual attention and the temporal dynamics of feature integration

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Two experiments studied the emergence of bindings between stimulus features (object files) and between stimulus and response features (event files) over time. Choice responses (R2) were signalled by the shape of a stimulus (S2) that followed another stimulus (S1) of the same or different shape, location, and colour. S1 did not require a response (Experiment 1) or trigger a precued simple response (R1) that was or was not repeated by R2 (Experiment 2). Results demonstrate that the mere cooccurrence of stimulus features, and of stimuli and responses, is sufficient to bind their codes. Bindings emerge quickly and remain intact for at least four seconds. Which features are considered depends on their task-relevance; hence, integration reflects the current attentional set. There was no consistent trend toward higher order interactions as a function of time or of the amount of attention devoted to S1, suggesting that features are not integrated into a single, global super-structure, but enter independent local bindings presumably subserving different functions.

OBJECT AND EVENT FILES

When an object appears before our eyes, its perceivable features are registered and coded in various areas in our brain—and yet, what we commonly perceive is not a mosaic bundle of attributes but a single, homogeneous object. This suggests the existence of some kind of feature-binding mechanism that keeps track of which feature goes with which, in such a way that features belonging to the same object can be integrated and cross-referenced in the process of internally reconstructing an observed external object (e.g., Allport, Tipper, & Chmiel, 1985; Singer, 1994; Treisman, 1996). In the visual domain, there is converging evidence for spontaneous feature integration from several lines of research.

First, Allport et al. (1985) had participants work through lists or sequences of superimposed pairs of letters or pictures. One member of a pair was the

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to-be-named target printed in a particular target colour (e.g., red), and the other member was a distractor printed in another colour (e.g., green). It turned out that reaction time (RT) substantially increased when, in a trial, the current target matched the preceding distractor as compared to trials with no match. One interpretation of this so-called negative priming effect (for overviews see Fox, 1995; May, Kane, & Hasher, 1995; Tipper, 2001) that was offered by Allport et al. is in terms of feature integration (for a revival of this theme see Neill, 1997; Park & Kanwisher, 1994). Assume that, in a given trial, both target and distractor features are integrated (i.e., linked across feature domains) separately, thus forming two different object representations. If then in the following trial the features appear in different combinations (e.g., when a formerly green letter now appears in red), integration is more difficult than for exact repetitions of feature combinations because it requires additional time to undo the already formed, and now misleading, cross-domain links. Although it seems clear by now that negative priming also involves processes unrelated to feature integration (such as inhibition of S–R links: Houghton & Tipper, 1994), there are various demonstrations of the unwanted retrieval of spontaneously integrated stimulus episodes (Kane, May, Hasher, Rahhal, & Stoltzfus, 1997; Lowe, 1985; Neill, 1997; Waszak, Hommel, & Allport, 2003).

Second, Kahneman, Treisman, and Gibbs (1992) presented participants with two displays in a sequence, a brief multiletter preview or prime display requiring no response (S1) and a single-letter probe display requiring verbal identification (S2). If the probe letter had already been presented somewhere in the preview display, probe identification was facilitated (a repetition benefit), but only slightly so and not in each experiment. However, if the previewed letter matched the probe both in identity and (absolute or relative) location, pronounced and stable identification benefits were observed. According to Kahneman et al., attending to a visual object establishes what they call an “object file”, an integrated episodic trace containing information about the relationship between object features and their location, possibly enriched by object-related knowledge from long-term memory. If an object file is constructed for a previewed object, and if this object re-appears at the same location, object perception does not require constructing a new file, but an update of the old one will do. That is, performance should not so much depend on the repetition of one or more stimulus features per se, but rather on whether the particular feature conjunction (e.g., of shape and location) is repeated or not. Only if the same conjunction reappears, the old object representation is used another time, thus speeding up the identification process. If, however, feature repetition is only partial or absent altogether, a new representation needs to be constructed, just as without a preview.

Third, Hommel (1998) had participants perform a binary-choice task in response to the shape of a stimulus (S2) that was preceded by another stimulus (S1) the features of which were irrelevant. In contrast to previous studies, the

experimental design allowed for an independent manipulation of the shape, location, and colour of S1 and S2, so that performance could be compared across several degrees and combinations of feature repetitions, ranging from a complete match of S1 and S2 (i.e., repetition of all possible features and feature conjunctions) to mismatch (i.e., no repetition of any feature or feature conjunction). Interestingly, the effects of feature repetitions were not independent of each other: Repeating shape produced better performance than alternation if colour was also repeated, but worse performance than alternation if colour alternated; and the same relationship was observed between shape and location. Given that complete matches yielded about the same performance as mismatches, these results do not so much point to a benefit of repeating a particular feature conjunction—as one would expect from Kahneman et al.'s (1992) approach—but rather suggest a cost of partial repetitions—as implied by Allport et al.'s (1985) account. Assume that being confronted with S1, say, a horizontal line at the bottom of a display, results in a spontaneous binding of the codes representing its shape and location, as depicted in Figure 1 (panel A). If S1 and S2 share either both shape and location (complete match) or none (mismatch), integrating S2 features should not represent any particular problem. However, if

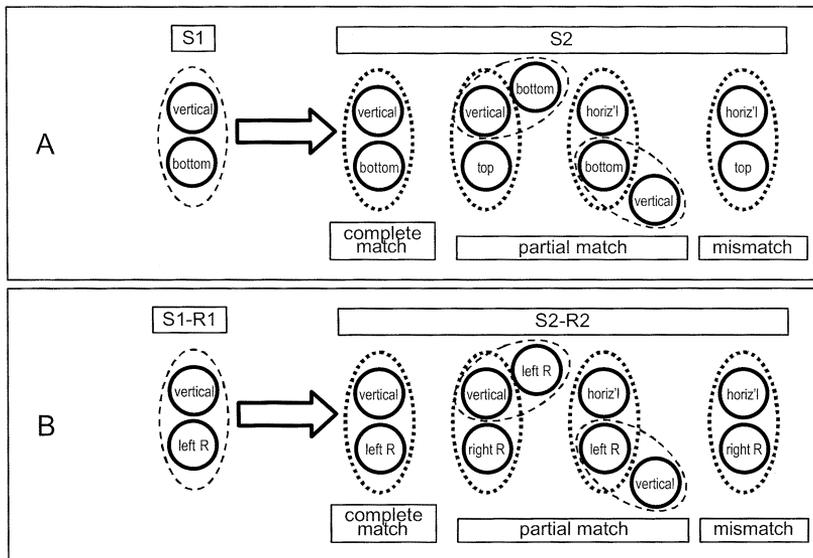


Figure 1. A binding account of partial-match costs. (A) The basic assumption is that feature codes representing Stimulus 1 (S1) are temporarily integrated into a coherent event representation. If relations between features of Stimulus 2 (S2) completely match or mismatch with these bindings, performance is unaffected. Partial matches, however, prime incorrect and misleading feature codes, which induces conflict and, thus, slows down performance. (B) The same logic applies to stimulus and response features.

only one but not the other feature overlaps (partial match), reactivating the code of the matching feature may spread activation to the code it has just been integrated with, thus impairing its integration with the actual feature.¹

Altogether, the available evidence strongly suggests that seeing an object results in the more or less spontaneous integration or binding of its features. Once bound together, these features (or their codes) apparently can no longer be separately addressed, so that perceiving a new combination of the same features requires another time-consuming rebinding process and/or the resolution of the conflict induced by the previous binding. Interestingly, these kinds of binding effects are not restricted to stimulus features. In the Hommel (1998) study, participants were precued, in each trial, whether the first response (R1) should be a left-hand or a right-hand key press. R1 was then triggered by the next upcoming stimulus (S1) without depending on any particular feature of it. One second after S1, S2 would appear, and participants were instructed to respond to its shape (or, in another experiment, to its colour) by pressing the left or right key (R2). Hence, participants performed sequences of a simple RT task followed by a binary-choice RT task, and what varied was the identity of R1 and R2 and the shape, colour, and location of S1 and S2. The results showed that the repetition or alternation of stimulus features did not only interact with other stimulus-feature effects, they also interacted with response repetition. For example, response repetitions were faster and more accurate if stimulus shape was also repeated than if shape alternated, whereas response alternations were faster and more accurate if shape alternated than if shape was repeated.

These findings imply that the binding logic introduced above also applies to combinations of stimulus and response features, along the lines sketched in Panel B of Figure 1: The mere cooccurrence of a stimulus feature and a response (feature) may lead to the creation of a binding between their codes, so that reactivating one will tend to prime the other. Indeed, there is converging evidence in support of this idea. For instance, Hommel (2003) found that, in a free-choice task, repeating the shape, colour, or location of the stimulus increases the likelihood that subjects repeat the previous response. Likewise, Dutzi and

¹ As pointed out by an anonymous reviewer, the logic underlying this account bears an interesting similarity to Kingstone's (1992) crosstalk interpretation of the combined effects of multiple cues on stimulus processing. Kingstone cued his subjects with regard to two features of an upcoming stimulus, such as spatial location and shape, or shape and colour. Unsurprisingly, valid cues sped up responses considerably but the cuing effects were not independent. In particular, performance was impaired if the stimulus matched one expectation but not the other, such as when an unexpected target form appeared in an expected colour or an expected form appeared in an unexpected colour. Kingstone suggests that people had created a "combined expectancy" that, if one part of the expectation is matched by the upcoming stimulus, primes the other, related part—which again facilitates processing stimuli that fully match the expectations but hamper the processing of partial matches. One may speculate that the cognitive structure people create when building a "combined expectancy" is the same as the "object file" that is left by integrating the features of a stimulus. In other words, anticipating an event may have the same effect as just having seen it before.

Hommel (2003) observed that producing a particular stimulus by pressing a particular key increases the likelihood that this key is pressed again if the same stimulus appears during the next trial. These findings suggest that feature integration may not be restricted to object perception but cross borders between perception and action to create what Hommel (1998) called “event files”.

PURPOSE OF STUDY

The available evidence points to the existence of object or event files, but the mechanisms underlying their creation, maintenance, and possible decay remain to be explored. The present study was motivated by three open questions that all in one or the other way refer to the temporal dynamics and the attentional preconditions of feature integration.

How complete is feature integration?

According to the original concept of an object file (Kahneman et al., 1992) one would assume that in the case of processing an object integration is well captured by the following scenario: Spatial attention is directed or attracted to a particular location in space and/or to an object occupying this location, and then all features of that object are integrated into a coherent object representation (e.g., Luck & Beach, 1998; Treisman, 1988, 1998). But are they? There is evidence that repeating conjunctions of letters and locations affect behaviour even if the letter case changes (Gordon & Irwin, 1996; Henderson, 1994). This suggests that feature integration may not be complete (e.g., may not necessarily include shape or shape details) but may be mediated by the task context. Likewise, Hommel (1998) found interactions between shape and location repetition only if shape was task relevant (by virtue of signalling S2) but not if colour was task relevant; and the opposite tendency was observed for colour–location interactions. Effects of task relevance were also obtained by Hommel (2003), who found evidence for location response bindings if the responses were defined in terms of location (left vs. right key) but not if they were defined in terms of number (single vs. double press).

To account for the impact of task relevance and context one may assume that feature codes enter more enduring representations only if, or to the degree that, they pass a kind of relevance or pertinence filter (e.g., Bundesen, 1990; Norman, 1968). That is, spatial attention may (or may not) preselect the features of an attended location or object, these features may then be weighted according to their relevance to the task at hand (in addition to possible bottom-up saliency factors), and the feature codes surviving these procedures will enter an object file. However, even this scenario does not appear to fully account for the available findings. For instance, the Hommel (1998) study revealed several indications of bindings between shape and location and between shape and colour, while colour and location were independent. Or, with respect to the

integration of stimulus and response features, colour was integrated with the response only if colour but not if shape was task relevant, whereas the signs of shape–colour integration were independent of whether shape or colour was relevant. Thus, not all features that have an effect (suggesting that they passed whatever filter had been applied) interact with each other, at least not in the form of a higher order interaction that would point to a comprehensive object or event file.

However, the reported studies used a very limited range of temporal intervals (or stimulus–onset asynchronies; SOAs) between the first, inducing display (S1) and the second, probe display (S2); e.g., all SOAs in the studies of Hommel (1998, 2003) employed SOAs of 1 s. Yet, the integration processes that presumably underlie the observed interactions between repetition effects might be rather time consuming, which implied that the construction of object or event representations is a temporally extended operation. If so, the findings reported so far may be just static snapshots of a dynamic binding process and, thus, represent arbitrarily chosen phases of this process only. To get a better idea of the temporal characteristics and possible limitations of feature integration we therefore manipulated SOA across a wide range of 200–4100 ms. One possibility would be that features are rapidly integrated into rather short-lived, transient bindings, so that signs for complete integration may be found with short, but not with long SOAs. Alternatively, integration may take time, which would imply that complete integration is found with long, but not with short SOAs.

Another variable that we thought might impact the completeness or depth of integration is the amount of endogenous attention allocated to S1 processing. In Hommel's (1998) original design S1 is entirely irrelevant, except that its presence needs to be noticed to trigger R1. On the one hand, this means that S1 cannot go unnoticed and, thus, must attract some degree of attention—the more so as it is the only event that occurs within a relatively long interval of 2.5 s. On the other hand, however, there is no need to fully process or even integrate the features of that stimulus, so that one might expect that processing is rather superficial. That feature repetition effects, and interactions between them, were nevertheless obtained indicates that the underlying binding processes do not strongly depend on the need or intention to integrate the particular features (although spatial attention may well be necessary in any case). However, integration may be deeper and more complete if it is really needed. Hence, it may well be that the lack of complete integration is merely a result of not requiring subjects to endogenously attend to S1 and perform operations that require the integration of its features. We tested this hypothesis by comparing an endogenously “unattended” condition designed after Hommel (1998) with an “attended” condition, where we required subjects to report S1 at leisure after R2 was completed. Apart from drawing more attention to S1, this manipulation is likely to require the consolidation of S1 features in short-term memory

(Jolicœur, Tombu, Oriet & Stevanovski, 2002), which has been claimed to be associated with feature integration (Luck & Vogel, 1997; Raffone & Wolters, 2001).

To summarize, we were interested to see whether higher order interactions of feature repetition effects (i.e., effects involving more than two features and/or the response) could be obtained by allowing more time for integration to proceed (i.e., at longer SOAs) and/or by increasing the attentional resources devoted to processing S1 (i.e., in the “attended” condition).

Are feature bindings addressed by location?

A second question that motivated our study concerns the way object or event files are addressed. According to the original suggestion of Kahneman et al. (1992), object files are addressed by location. That is, encountering an object leads to the retrieval of that object file that includes spatial codes that match the location of the present object to at least some degree. However, developmental research provides evidence that infants and children often use (changes in) nonspatial features to individuate objects and spatiotemporally extended events, suggesting that object representations can be addressed in ways that are not mediated by location codes (e.g., Leslie & Kaldy, 2001; Leslie, Xu, Tremoulet, & Scholl, 1998). Moreover, the addressing-by-location assumption implies that information about object location must be a basic ingredient of object files, which does not fit with Hommel’s (1998, 2003) observations of feature interactions not involving location repetition.

One possible conclusion from these findings is that the outcome of binding processes is not so much a single representational entity collecting all information about a particular event, as the object-file metaphor would suggest, but rather a distributed network of local bindings presumably subserving diverse functions (Hommel, 1998, 2003). Alternatively, to take up the argument developed above, the available findings may represent only a snapshot of a more dynamic integration process. For instance, integration may begin locally, connecting pairs of feature codes, and only gradually build up a global event representation. If so, we might find changes in the order of interactions obtained across SOA, lower order interactions dominating at short SOAs and increasingly higher order interactions (including stimulus location) at longer SOAs. And, again, the amount of attentional resources devoted to processing the integrated event (i.e., S1) might play a mediating role.

How are feature priming and feature integration related?

A third question underlying our study has to do with the relationship between feature priming and feature integration. Apart from evidence of integration Kahneman et al. (1992) were also interested in what they called *nonspecific*

effects, that is, effects due to the repetition or alternation of a single stimulus feature, independent of any interaction with another feature. Little evidence for such effects was found by Kahneman et al. or Hommel (1998). However, substantial priming effects were obtained in the studies of Gordon and Irwin (1996), Henderson (1994), and Henderson and Anes (1994), where repeating nonspatial stimulus features significantly improved performance even if the stimulus changed location in between two appearances. Gordon and Irwin, for instance, had subjects make word–nonword judgements to target stimuli that randomly appeared in one of two vertically arranged boxes. Each stimulus was preceded by two prime words, and in some cases one of these primes matched the target stimulus (e.g., “doctor” + “bread” → “doctor”). Matching primes sped up reaction times substantially, in particular if prime and target appeared in the same box (i.e., shared location). This supports the assumption that processing the prime was accompanied by some sort of integration of its identity and its location, and that the product of this integration was maintained at least until target presentation. However, priming effects were smaller but still reliable even if the matching prime had appeared in the box opposite to the target, suggesting that retrieving prime information did not require the repetition of location. Hence, nonspecific priming does exist, at least under some circumstances. Kahneman et al. attributed the absence of nonspecific effects in their study to the small number of stimulus alternatives they had used: The same items were presented over and over again, so that their codes may have been primed to ceiling. However, given that Henderson and colleagues obtained nonspecific priming with even smaller stimulus sets, this is a rather unlikely explanation.

Again, the time interval between the first and the second presentation of the stimuli may be an important factor. Indeed, the studies where priming effects were weak or absent all used rather long SOAs (Hommel, 1998: 1000 ms; Kahneman et al., 1992, Exps. 1 and 2: 400–950 ms), whereas studies where reliable effects were observed employed short SOAs (Gordon & Irwin, 1996: SOAs of 1500 ms but interstimulus intervals of only 250 ms; Henderson, 1994: the latency of a saccade). It is therefore possible that the priming of codes of individual features is a rather short-lived phenomena that is observable with very brief SOAs only (cf. Hommel, 1994). If so, we would expect priming effects with short, but not with longer, SOAs.

EXPERIMENTS 1 AND 2

We conducted two very similar experiments to address our three guiding questions. Experiment 2 was closely modelled after Hommel (1998): Subjects were cued to prepare a left- or right-hand key press (R1), which they carried out as soon as S1—the priming stimulus—was presented (see Figure 2). Even though it was only the presence but not the identity of S1 that counted for performing R1, we varied its shape, colour, and (vertical) location. After a

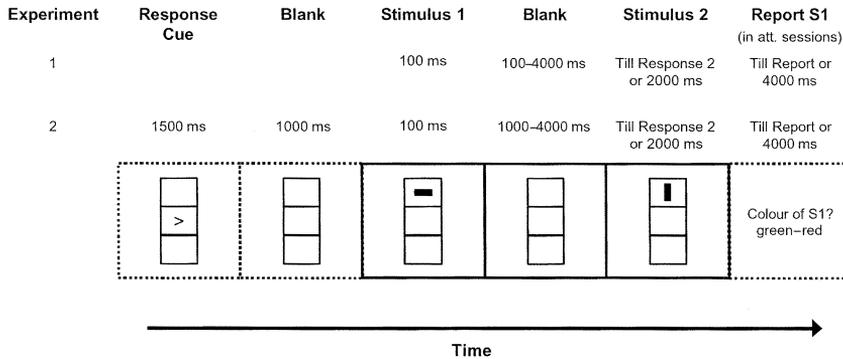


Figure 2. Overview of the displays and the timing of events in Experiments 1 and 2.

variable SOA (1100, 2100, or 4100 ms) S2 appeared to signal R2. The two alternative shapes of S2 were mapped onto the two R2 alternatives, while colour and location of S2 were entirely irrelevant to the task—which was pointed out to the subjects. In one half of the sessions (the *attended* sessions), subjects were also to report one randomly chosen (i.e., unpredictable) feature of S1 after R2 was completed, a manipulation that we considered to draw (more) attention to S1 and to motivate if not require the integration of its features.

We were particularly interested in three types of effects and their dependencies on our manipulations of attention and SOA. First, we wanted to see whether priming effects, i.e., effects of the repetition of an individual feature, would occur and, if so, whether they might be more pronounced at short than at long SOAs. Note, however, that even the shortest SOA of Experiment 2 was longer than our above considerations suggest is optimal for finding priming effects, which was the main reason for us to conduct Experiment 1 (see below). Second, we were interested to see whether the interactions between effects of stimulus-feature repetitions (e.g., Shape \times Colour) obtained by Hommel (1998) can be replicated and, even more important, whether they would be affected by the amount of attention devoted to S1 and change across SOA. Of particular theoretical relevance were interactions between more than two stimulus features (which would point to complete integration) and/or of interactions not involving stimulus location (which would speak to the addressing-by-location issue), and possible changes of these interactions as a function of attention (which might create more complete bindings) and SOA (which might allow for the creation of increasingly global bindings). Third, we sought to replicate the interactions between stimulus features and response obtained by Hommel (1998). And, again, we were interested in whether these interactions remain stable across attentional manipulations and SOA or, rather, whether they would enter higher order interactions as attentional investment and SOA increases.

As pointed out, Experiment 2 with its long SOAs was unlikely to provide an optimal platform for priming effects, which can be expected to occur in the range of 0–500 ms. However, using that short SOAs would create a dual-task situation in which the S2–R2 component of the task would temporally overlap with the S1–R1 component. This would be likely to create unpredictable and complicating side effects, such as dual-task costs or S1–R2 and S2–R1 integration (cf. Dutzi & Hommel, 2003), which we wanted to avoid. To do so we restricted the whole first part of each trial to the presentation of S1 (see Figure 2), which now, at least in unattended sessions, had no function at all. That is, people were presented with two stimuli in a row, separated by a variable SOA (200–4100 ms), and responded to the second stimulus (S2) by pressing a left or right key (R2—which in the absence of R1 was the only response!). As this modification eliminated R1, Experiment 1 did not speak to the integration of stimulus and response features. However, including a short SOA increased our chances to detect short-lived phenomena in the priming and integration of stimulus features.

Method

Participants

Seventeen students of the Leiden University took part for pay in Experiment 1 and 16 participated in Experiment 2. All reported having normal or corrected-to-normal vision, and were not familiar with the purpose of the experiment.

Apparatus and stimuli

The experiments were controlled by a Targa Pentium III computer, attached to a Targa TM 1769-A 17-inch monitor. Participants faced three grey square outlines, vertically arranged, as illustrated in Figure 2. From viewing distance of about 60 cm, each of these frames measured $2.6^\circ \times 3.1^\circ$. A thin vertical line ($0.1^\circ \times 0.6^\circ$) and a somewhat thicker horizontal line ($0.3^\circ \times 0.1^\circ$) served as S1 and S2 alternatives, which were presented in red or green in the top or bottom frame. Response cues (in Experiment 2 only) were presented in the middle frame (see Figure 2), with rows of three left- or right-pointing arrows indicating a left and right key press, respectively. Responses to S1 (in Experiment 2 only) and to S2 were made by pressing the left or right shift key of the computer keyboard with the corresponding index finger.

Procedure and design

Experiment 1. This consisted of six 1 hour sessions: Three S1 unattended and three S1 attended. In (endogenously) *unattended* sessions participants made a single response on each trial, a binary-choice reaction to the second of two successive stimuli. Half of the participants responded to the vertical and the

horizontal line by pressing the left and right key, respectively, while the other half received the opposite mapping. In *attended* sessions participants were, after each binary-choice reaction to a S2, probed for their memory of a feature of S1. They were presented with one of three questions, asking for the shape, colour, or location of S1 (e.g., “What was the colour of Stimulus 1?” in Dutch). Two words indicating the two response alternatives (“horizontal–vertical”, “red–green”, or “top–bottom”, in Dutch) were presented below the question, with their relative position indicating the mapping of alternatives onto the left and right shift key. The six combinations of the three stimulus dimensions and two alternative key mappings were presented in pseudorandom sequence but equally often within one session. Half of the participants began with the unattended sessions; the other half began with the attended sessions.

The sequence of events is shown in the upper row of Figure 2. In unattended sessions, the intertrial interval of 2000 ms was followed by a 100 ms appearance of S1. The duration of the next, blank interval depended on the SOA condition: 100, 1000, 2000, or 4000 ms. Then S2 appeared and stayed until the response was given or 2000 ms had passed. If the response was incorrect auditory feedback was presented. In attended sessions, this sequence of events was followed by the memory probe question, which stayed until the response was given or 4000 ms had passed.

Each session comprised 256 trials, composed by a factorial combination of the two shapes (vertical vs. horizontal line), colours (red vs. green), and locations (top vs. bottom) of S2, the repetition vs. alternation of shape, colour, and location, and the four SOAs ($2 \times 2 \times 2 \times 2 \times 2 \times 4 = 256$). Thus, taken together, the three attended and three unattended sessions of Experiment 1 amounted to 1536 trials. Participants were allowed to take a short break during each session.

Experiment 2. This consisted of six 90 minute sessions: Three unattended and three attended sessions. The procedure was as in Experiment 1, with the following exceptions. In unattended session 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 shape, colour, or location. 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. As in Experiment 1, R2 was a binary-choice reaction to the shape of S2 and attended sessions required the identification of a randomly selected feature of S1.

The sequence of events in each trial is shown in the lower row of Figure 2. Next to the intertrial of 2000 ms a response cue signalled R1 for 1500 ms, followed by a blank interval of 1000 ms. Then S1 appeared for 100 ms, followed by a further blank interval the duration of which depended on the SOA con-

dition: 1000, 2000, or 4000 ms. If R1 was incorrect or not given within 600 ms the trial started again. After the respective SOA, S2 appeared and stayed until R2 was given or 2000 ms had passed.

Each session comprised 384 trials, composed by a factorial combination of the two shapes (vertical vs. horizontal line), colours (red vs. green), and locations (top vs. bottom) of S2, the repetition vs. alternation of shape, colour, location, and the response, and the three SOAs ($2 \times 2 \times 2 \times 2 \times 2 \times 2 \times 2 \times 3 = 384$). Thus, taken together, the six sessions of Experiment 2 amounted to 2304 trials.

Results and discussion

Analytical procedures. Trials with missing or anticipatory responses (1.4% in Experiment 1 and 1.8% in Experiment 2) were excluded from the analysis. We also excluded trials in which the memory probe response was incorrect. From the remaining data, mean RTs and proportions of errors (PEs) for R2 (i.e., the response to S2) were further analysed, as well as PEs for responses in the memory probe task (available from attended sessions only).

In Experiment 1, means were computed as a function of Attention (S1 unattended vs. attended), the four SOAs, and the three possible relationships between the two stimuli in each trial, that is, repetition vs. alternation of stimulus shape, colour, or location (see Table 1 for means). ANOVAs were performed by using a four-way design (in case of the memory data) and a five-way design for repeated measures. The significance criterion for all analyses was set to $p < .05$.

In Experiment 2, means were computed as a function of Attention (S1 unattended vs. attended), the three SOAs, and the four possible relationships between the two responses (R1 and R2) and the two stimuli in each trial, that is, repetition vs. alternation of response, stimulus shape, colour, or location (see Table 2 for means). ANOVAs were performed by using a five-way design (in case of the memory data) and a six-way design for repeated measures.

We first analysed the memory-probe data. Experiment 1 revealed only two reliable effects, one indicating that errors increased with SOA (3.7%, 4.3%, 4.8%, 5.4%), $F(3, 48) = 3.18$, $p < .05$, and the other that fewer errors were made with repetitions of stimulus location than alternations (4.1 % vs. 5.0%), $F(1, 16) = 8.15$, $p < .05$. These effects were not replicated in Experiment 2 ($F_s < 1.1$) where, however, Shape was involved in two effects: In a main effect, $F(1, 15) = 12.73$, $p < .005$, and an interaction with SOA, $F(2, 30) = 10.74$, $p < .001$. When shape was repeated, the errors followed the same pattern as in Experiment 1, i.e., they increased with SOA (3.4%, 3.9%, and 5.1%). When shape alternated, however, this pattern was not observed (5.9%, 5.2%, and 5.2%). Taken together, the only replicable outcome seems to be the increase in errors as SOA increases. As in our design SOA is confounded with the effective retention interval of the memory task, this is an unsurprising observation. More important, however, the

TABLE 1
 Experiment 1: Means of mean reaction times for responses to Stimulus 2 (RT_{R2} ; in Ms) and percentages of errors on R2 (PE_{R2}) and on the report of S1 in attended sessions (PE_M), as a function of attention to Stimulus 1, stimulus-onset asynchrony (in Ms), and the feature match between Stimulus 1 and Stimulus 2

		<i>Stimulus-onset asynchrony</i>							
		200		1100		2100		4100	
Repeated	RT_{R2}	PE_{R2}	PE_M	RT_{R2}	PE_{R2}	PE_M	RT_{R2}	PE_{R2}	PE_M
<i>Stimulus 1 unattended</i>									
Neither	560	7.10		532	4.41		533	3.18	
S(hape)	544	5.39		542	5.75		538	4.78	
L(ocation)	558	5.27		554	4.71		548	4.71	
C(olour)	554	5.51		544	4.65		539	4.71	
SL	553	5.75		551	5.27		543	4.29	
SC	543	5.27		542	4.78		534	4.16	
LC	558	5.63		557	4.29		544	4.29	
SLC	553	6.37		553	3.67		536	3.18	
<i>Stimulus 1 attended</i>									
Neither	731	12.50	3.70	676	6.61	5.82	604	6.12	5.86
S	700	7.35	4.51	660	5.82	3.98	642	4.78	4.53
L	712	8.02	5.07	660	5.14	5.33	635	5.21	5.32
C	708	8.02	4.27	658	5.21	3.53	631	4.96	6.08
SL	693	6.98	2.78	660	5.63	3.79	641	4.79	5.61
SC	693	6.61	3.12	657	5.14	4.91	638	4.65	4.94
LC	705	8.08	3.75	661	5.51	3.11	641	5.27	3.34
SLC	686	7.10	2.13	658	5.14	3.95	640	4.90	2.52
							596	4.41	4.66
							617	4.47	7.69
							615	4.78	5.52
							609	5.20	7.26
							612	4.04	3.45
							613	3.67	5.04
							617	5.39	4.10
							615	3.67	5.42

overall memory performance was very good, demonstrating that our attention manipulation worked.

Tables 3 and 4 provide an overview of the ANOVA outcomes for RTs and PEs obtained for R2 in Experiments 1 and 2, respectively. To facilitate access to the relatively complex data pattern we sort, present, and discuss the outcomes according to their theoretical implications, attempting to integrate the findings from Experiments 1 and 2 as far as possible.

TABLE 3
Results of analysis of variance on mean reaction time of correct responses (RT) and percentage of errors (PE) for Experiment 1

<i>Effect</i>	<i>df</i>	<i>RT_{R2}</i>		<i>PE_{R2}</i>	
		<i>MSE</i>	<i>F</i>	<i>MSE</i>	<i>F</i>
Attention (Att)	1,16	172,690.22	18.95**	137.21	1.88
Soa	3,48	9,125.63	19.38**	36.77	8.17**
Shape (Shp)	1,16	4,674.04	0.49	67.29	1.20
Colour (Col)	1,16	633.68	2.15	14.67	2.83
Location (Loc)	1,16	3,271.31	6.60*	36.24	2.35
Att × Soa	3,48	8,477.65	12.75**	21.72	6.74**
Att × Shp	1,16	2,439.05	1.77	43.96	1.10
Att × Col	1,16	992.95	1.69	9.28	0.21
Att × Loc	1,16	1,499.61	7.94*	13.32	0.03
Soa × Shp	3,48	1,589.84	9.38**	33.95	3.00*
Soa × Col	3,48	956.16	0.49	12.56	0.81
Soa × Loc	3,48	1,263.26	1.19	19.73	0.67
Shp × Col	1,16	740.39	3.99	31.73	5.97*
Shp × Loc	1,16	1,553.19	5.32*	29.28	0.03
Col × Loc	1,16	894.73	1.97	9.38	9.06**
Shp × Col × Loc	1,16	924.86	0.04	32.15	0.02
Att × Soa × Shp	3,48	1,077.24	4.85**	17.36	1.51
Att × Soa × Col	3,48	751.51	1.83	20.60	0.64
Att × Soa × Loc	3,48	551.69	2.52	17.94	0.25
Att × Shp × Col	1,16	920.68	0.24	16.76	0.34
Att × Shp × Loc	1,16	940.20	2.99	21.98	0.32
Att × Col × Loc	1,16	299.16	10.05**	27.26	2.18
Att × Shp × Col × Loc	1,16	180.18	0.96	15.20	0.88
Soa × Shp × Col	3,48	897.30	0.54	19.28	1.78
Soa × Shp × Loc	3,48	1,088.54	2.52	17.74	2.30
Soa × Col × Loc	3,48	536.03	1.66	21.02	1.03
Att × Soa × Shp × Col	3,48	982.75	0.25	18.53	0.74
Att × Soa × Shp × Loc	3,48	916.00	1.78	26.72	0.35
Att × Soa × Col × Loc	3,48	740.09	0.59	11.86	0.52
Soa × Shp × Col × Loc	3,48	778.49	0.93	23.75	1.85
Att × Soa × Shp × Col × Loc	3,48	1,066.25	0.21	18.72	0.57

Soa = stimulus-onset asynchrony. * $p < .05$, ** $p < .01$.

TABLE 4
Results of analysis of variance on mean reaction time of correct responses (RT) and percentage of errors (PE) for Experiment 2

<i>Effect</i>	<i>df</i>	<i>RT_{R2}</i>		<i>PE_{R2}</i>	
		<i>MSE</i>	<i>F</i>	<i>MSE</i>	<i>F</i>
Attention (Att)	1,15	87,301.63	28.65**	484.85	3.08
Soa	2,30	8,029.66	50.22**	28.34	10.51**
Shape (Shp)	1,15	2,870.28	7.02*	70.50	2.58
Colour (Col)	1,15	970.91	0.60	56.07	0.69
Location (Loc)	1,15	1,272.91	2.45	41.17	0.01
Att × Soa	2,30	3,889.28	12.39**	36.97	0.26
Att × Shp	1,15	2,528.90	9.62**	21.75	7.08*
Att × Col	1,15	1,295.73	0.42	24.66	0.57
Att × Loc	1,15	751.230	0.12	14.30	0.95
Soa × Shp	2,30	1,172.57	1.83	40.10	3.99*
Soa × Col	2,30	984.09	0.39	26.31	1.38
Soa × Loc	2,30	650.91	5.07*	38.14	1.20
Shp × Col	1,15	1,482.39	0.16	35.51	0.03
Shp × Loc	1,15	1,101.04	25.49**	45.20	8.40*
Col × Loc	1,15	873.06	0.02	34.93	1.46
Shp × Col × Loc	1,15	1,147.65	8.38*	18.35	0.01
Att × Soa × Shp	2,30	905.82	0.06	21.61	0.88
Att × Soa × Col	2,30	1,110.85	0.24	19.53	2.06
Att × Soa × Loc	2,30	690.31	4.72*	25.35	1.06
Att × Shp × Col	1,15	827.05	0.36	20.47	0.68
Att × Shp × Loc	1,15	956.80	0.75	46.14	0.07
Att × Col × Loc	1,15	527.00	0.08	14.04	0.07
Att × Shp × Col × Loc	1,15	1,444.94	0.49	16.25	0.97
Soa × Shp × Col	2,30	662.73	2.10	32.10	2.09
Soa × Shp × Loc	2,30	975.07	2.87	24.37	9.46**
Soa × Col × Loc	2,30	699.83	1.39	29.97	0.98
Att × Soa × Shp × Col	2,30	851.50	0.43	20.07	1.68
Att × Soa × Shp × Loc	2,30	1,024.38	0.11	32.49	0.38
Att × Soa × Col × Loc	2,30	694.14	1.81	19.71	0.12
Soa × Shp × Col × Loc	2,30	811.98	2.99	27.27	1.76
Att × Soa × Shp × Col × Loc	2,30	773.77	0.50	18.75	5.02*
Response (Rsp)	1,15	9,560.97	0.02	157.79	0.01
Att × Rsp	1,15	3,802.59	1.10	24.10	1.97
Soa × Rsp	2,30	1,167.12	5.56**	36.13	7.38**
Shp × Rsp	1,15	3,945.80	76.38**	90.20	84.80**
Col × Rsp	1,15	517.22	36.56**	16.50	13.20**
Loc × Rsp	1,15	1,334.64	50.99**	97.38	33.44**
Shp × Col × Rsp	1,15	740.11	7.15*	15.34	0.26
Shp × Loc × Rsp	1,15	1,047.71	0.11	22.22	11.03**
Col × Loc × Rsp	1,15	779.90	2.65	23.90	0.73
Shp × Col × Loc × Rsp	1,15	1,164.77	2.54	22.41	4.34

(Continued)

TABLE 4
(Continued)

<i>Effect</i>	<i>df</i>	<i>RT_{R2}</i>		<i>PE_{R2}</i>	
		<i>MSE</i>	<i>F</i>	<i>MSE</i>	<i>F</i>
Att × Shp × Rsp	1,15	1,675.06	20.23**	62.03	1.57
Att × Col × Rsp	1,15	1,183.53	0.04	51.04	0.62
Att × Loc × Rsp	1,15	1,128.56	6.59*	40.21	1.25
Att × Shp × Col × Rsp	1,15	584.54	8.88**	19.62	0.16
Att × Shp × Loc × Rsp	1,15	459.34	1.38	19.55	6.89*
Att × Col × Loc × Rsp	1,15	762.97	0.21	19.05	13.20**
Att × Shp × Col × Loc × Rsp	1,15	964.95	0.13	41.15	0.24
Att × Soa × Rsp	2,30	978.28	2.06	31.92	0.83
Soa × Shp × Rsp	2,30	1,347.20	24.61**	37.41	29.81**
Soa × Col × Rsp	2,30	756.06	1.77	20.07	1.77
Soa × Loc × Rsp	2,30	1,750.25	2.49	34.29	7.34**
Soa × Shp × Col × Rsp	2,30	715.33	1.77	21.71	1.91
Soa × Shp × Loc × Rsp	2,30	525.65	7.81**	26.66	1.71
Soa × Col × Loc × Rsp	2,30	637.76	0.91	16.30	1.16
Soa × Shp × Col × Loc × Rsp	2,30	1,008.73	1.51	29.15	1.77
Att × Soa × Shp × Rsp	2,30	739.84	1.30	20.75	3.84*
Att × Soa × Col × Rsp	2,30	970.00	0.12	19.10	0.64
Att × Soa × Loc × Rsp	2,30	1,021.53	1.93	32.86	0.15
Att × Soa × Shp × Col × Rsp	2,30	598.73	0.12	32.73	1.71
Att × Soa × Shp × Loc × Rsp	2,30	774.01	0.75	24.44	1.82
Att × Soa × Col × Loc × Rsp	2,30	482.65	0.79	24.79	0.03
Att × Soa × Shp × Col × Loc × Rsp	2,30	572.13	0.45	12.66	0.45

Soa = stimulus-onset asynchrony. * $p < .05$, ** $p < .01$.

First, we address effects that are not specific to the repetition or alternation of particular stimulus or response features, that is, main effects of, and interactions between the attention factor and SOA. As these effects reflect the impact of task overlap, we call them *multiple-task effects*.

Second, we address effects that are restricted to the repetition or alternation of a single stimulus or response feature, either in form of a main effect or in interaction with Attention or SOA. These effects are likely to reflect some kind of priming, i.e., leftover activation of a feature code, or some action triggered by that (e.g., inhibition of return with location repetitions). We thus call them *priming effects*.

Third, we consider interactions *between* effects of stimulus-feature repetitions or alternations. Such effects show that the impact of repeating a particular feature depends on the repetition or alternation of another feature, which implies that the corresponding feature codes act as a unit. As we take this to reflect the integration of feature codes we call those effects *stimulus-integration effects*.

Finally, we discuss interactions between the effects of repeating or alternating one or more particular stimulus feature(s) on the one hand and the effect of repeating or alternating the response. To the degree that such effects can be observed (which is only possible in Experiment 2) they can be taken to imply the integration of features across perception and action, which is why we call them *stimulus–response-integration effects*.

Multiple-task effects. Figure 3 gives an overview of the impact of our attentional manipulation (i.e., the memory probe task) and of SOA on RTs and PEs in Experiments 1 and 2. Introducing the memory task produced pronounced RT costs without increasing the error rates reliably—even though a numerical trend is obvious in the errors from Experiment 2. SOA had a strong impact as well by increasing both RTs and errors at shorter SOAs. This impact was modified by attention–SOA interactions, which affected both measures from Experiment 1 and RTs from Experiment 2. As Figure 3 shows, the interference from the memory task is particularly strong at the shortest SOA of Experiment 1.

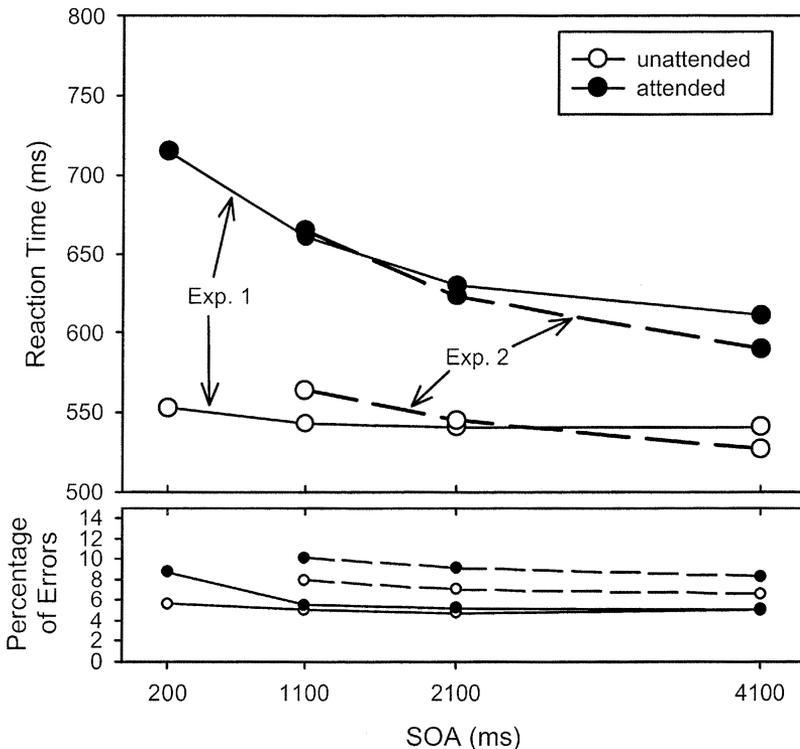


Figure 3. Reaction times and percentage of errors in Experiments 1 (straight lines) and 2 (broken lines), as a function of stimulus–onset asynchrony (SOA) and attention (S1 unattended vs. attended).

Similar effects have been observed in a couple of recent studies by Jolicoeur and colleagues, summarized in Jolicoeur, Dell'Acqua, and Crebolder (2000). For instance, Jolicoeur and Dell'Acqua (1998) found that having subjects encode between one and three masked letters for later report delays a binary-choice response to a tone the more the more letters are encoded and the shorter the SOA between letter and tone is. They attribute this effect to the need to consolidate stimulus information into some short-term store before a concurrent task can be taken on or pursued. Even though our stimuli were not masked it is reasonable to assume that S1 was also consolidated for the later memory probe, which delayed responding to S2 in attended conditions if SOA was short.

However, consolidation is unlikely to account for all aspects of our findings. In particular, RTs from both experiments and the errors in Experiment 2 provide evidence of performance costs in the attended condition that do not disappear at longer SOAs, that is, performance in this condition reaches its asymptote at a level that is considerably lower (or higher, in terms of RT and PE) as that reached in unattended conditions. Hints towards similar differences in asymptote were also obtained in the Jolicoeur and Dell'Acqua (1998) study, but only with memory loads of more than one item. One explanation for this difference might be that Jolicoeur and Dell'Acqua's task required the report of only one feature per item (e.g., the letter name) whereas we required subjects to maintain three features. If so, we would need to compare our findings with Jolicoeur and Dell'Acqua's three-item condition, and here even these authors found differences in asymptote. The only problem with this interpretation is that findings by Luck, Vogel, and colleagues (Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001) suggest that what matters for memory performance is the number of items but not the number of their features. However, the main focus of these authors was on memory limitations rather than on the impact of memory processes on performance in concurrent tasks, and their results do not rule out that this impact increases as a function of features. Also, they took care to prevent subjects from verbally encoding the items, whereas verbal encoding was certainly an option in our experiments. If our subjects had used this option, maintaining three features would in fact have implied the storage of three different items, which again would fit with the observation that our findings compare well with those of Jolicoeur and Dell'Acqua's three-item condition.

In summary, our findings reflect two types of intertask interference. One is restricted to short SOAs, where the memory task creates particularly visible performance deficits in the RT task, presumably due to the consolidation of S1-related codes. The other type of interference is also induced by the memory task but affects performance across the whole SOA range tested. These dual-task costs are likely to stem from processes responsible for the maintenance of feature-related information. Most important for our present purposes, the memory probe task produced considerable effects, which suggests it was successful in inducing increased attention to S1.

Priming effects. Figure 4 gives an overview of the effects of repeating versus alternating single stimulus features, as a function of attention to S1 and SOA. Let us first focus on *shape*, the only stimulus feature that was nominally relevant for the S2–R2 task. As expected, repeating shape produced benefits at the shortest SOAs, and this benefit was further boosted by increasing attention to S1. This pattern is reflected in the reliable interactions of shape repetition with attention and SOA obtained in Experiment 1 and in the two-way interactions of shape with attention and with SOA in Experiment 2. But there is a second, negative effect that is confined to the attention condition and the longer SOAs (and, with regard to errors, to Experiment 2). Such reversals from positive to negative repetition effects are a common observation (e.g., Kirby, 1980; Kornblum, 1973). The received view is that positive and negative effects are due to different processes: While the former reflect automatic priming from leftover activation of the codes of the preceding stimulus or response, the latter represents a more strategic expectation bias towards stimulus (or response) alternation (e.g., Soetens, Boer, & Huetting, 1985). If so, one would indeed predict that such “later”, negative repetition effects would be restricted to conditions where the event the alternation bias is based on was attended.

For *colour*, no reliable main effect or interaction involving attention or SOA was obtained, even though Figure 4 hints to a possible priming effect at the shortest SOA. As the following sections will provide evidence that S1 colour was processed, we attribute the absence of colour-related priming effects to the fact that colour was not task relevant (cf. Hommel, 1998), neither directly nor, as we will explain below, indirectly.

The *location* stimulus was involved in several RT effects. In Experiment 1, there was an overall cost of location repetitions that was more pronounced in the unattended condition. This pattern likely reflects inhibition of return (IoR), the widespread observation that attending to an actually irrelevant stimulus impairs later responses to relevant stimuli appearing in the same location (e.g., Maylor, 1985; Posner & Cohen, 1984). Experiment 2 shows a different pattern resulting in an interaction of location and SOA, modified by a three-way interaction with attention. The former reflects the transition of a positive into a null or even negative effect as SOA increases, while the latter indicates that this tendency was restricted to the attended condition. In the absence of further evidence we hesitate to interpret these numerically very small effects. However, it is interesting to note that both attention conditions of Experiment 2 yielded results that are similar to those from the attended condition of Experiment 1. This might indicate that having people to respond to a stimulus releases it from producing IoR even though neither the identity of the stimulus nor its location matters for the task at hand. Another interesting observation is that location repetition effects affected RTs only but not error rates. Such a finding is consistent with claims that IoR does not impair the processing of the stimuli that appear at a

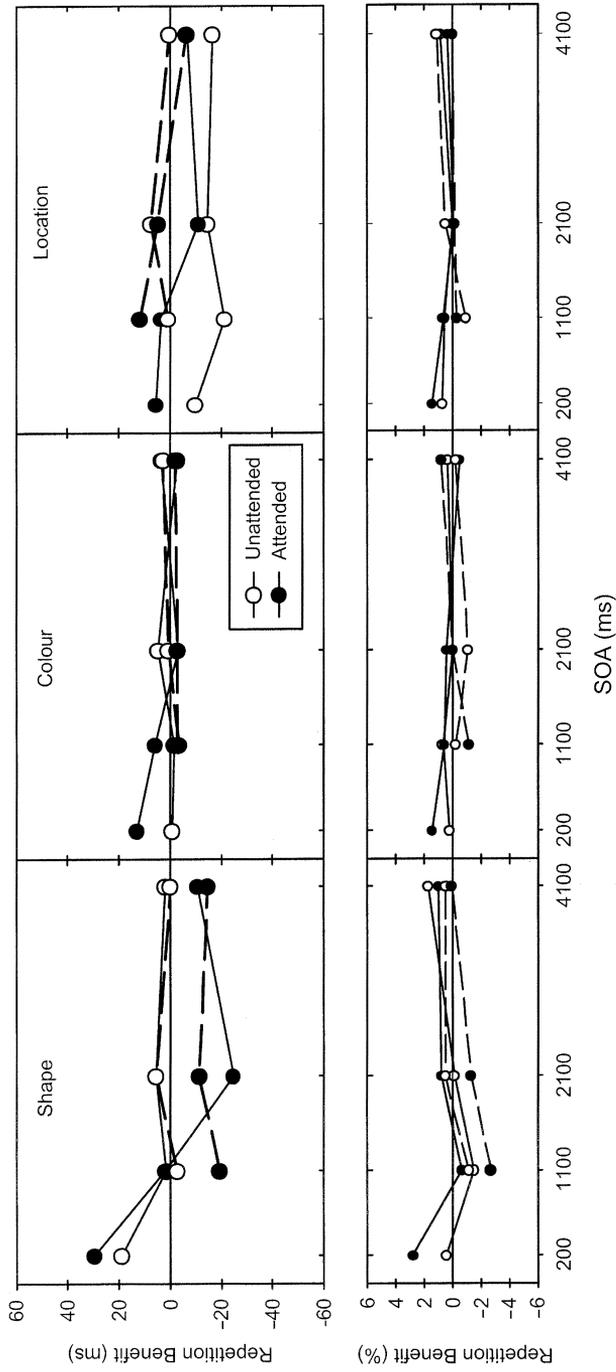


Figure 4. Repetition benefits ($RT_{\text{alternation}} - RT_{\text{repetition}}$, $PE_{\text{alternation}} - PE_{\text{repetition}}$) in Experiments 1 (straight lines) and 2 (broken lines), as a function of stimulus-onset asynchrony (SOA) and attention (S1 unattended vs. attended).

previously cued location but only slows down responding to them (Fuentes, Vivas & Humphreys, 1999; Taylor & Klein, 2000).

Finally, *response* repetition (which was involved in Experiment 2 only) did not yield a main effect or an interaction involving attention, but it did interact with SOA. Whereas the 1100 ms SOA produced benefits of response repetitions in RTs (610 and 619 ms, for repetition and alternation, respectively) and PEs (8.2% and 9.8%), the 2100 ms SOA yielded no difference (584 vs. 583 ms and 8.2% vs. 7.9%, respectively), and the longest SOA produced a disadvantage of repetitions (561 vs. 556 ms and 8.1% vs. 6.9%, respectively). As in the case of shape repetitions, this pattern is consistent with the assumption of an automatic priming component of repetition effects, predominant at short SOAs, and a strategic expectation bias that emerges at longer SOAs (Soetens et al., 1985).

In summary, standard priming effects with repetition benefits at short and alternation benefits (i.e., repetition disadvantages) at longer SOAs were observed for stimulus-shape and response repetition. Stimulus location merely showed evidence of an IoR-type pattern if S1 was not attended or relevant in any way, and stimulus colour showed no reliable effect at all.

Stimulus-integration effects. Across the two experiments, we obtained four clusters of results that involved interactions between stimulus-feature repetition effects. The first is actually a single finding from Experiment 1, showing that *shape* and *colour* had an interactive effect on PEs. This effect exhibited the typical crossover pattern with better performance for colour repetitions if shape was also repeated than if it was alternated (4.7% vs. 6.1%) but worse performance for colour alternations if shape was repeated than if it was alternated (5.9% vs. 5.6%). The corresponding RT effect followed a similar pattern but did not reach significance. It may be interesting to note that we have often observed this effect in both published (Hommel, 1998) and unpublished studies, and it often turns out to either just pass or just not pass the significance criterion. A possible explanation of this notorious unreliability may be that people integrate the irrelevant colour of a stimulus with its relevant shape to the degree that the colour is sufficiently salient—assuming that what counts as sufficient varies from subject to subject. This would suggest that which features are integrated depends on both top-down factors with a preference for task relevant information and bottom-up factors that attract attention in an automatic fashion (Dutzi & Hommel, 2003). We will get back to this issue below.

The second cluster involves interactions between *shape* and *location*. These factors produced two-way interactions in both experiments. The pattern was as expected—better performance for shape and location repeated, and shape and location alternated, than for partial matches; hence, combinations of one being repeated and the other alternated (see Figure 5). However, in case of the PEs in Experiment 2, the interaction was further modified by SOA. Separate ANOVAs confirmed that this was due to the two-way interaction being significant for the

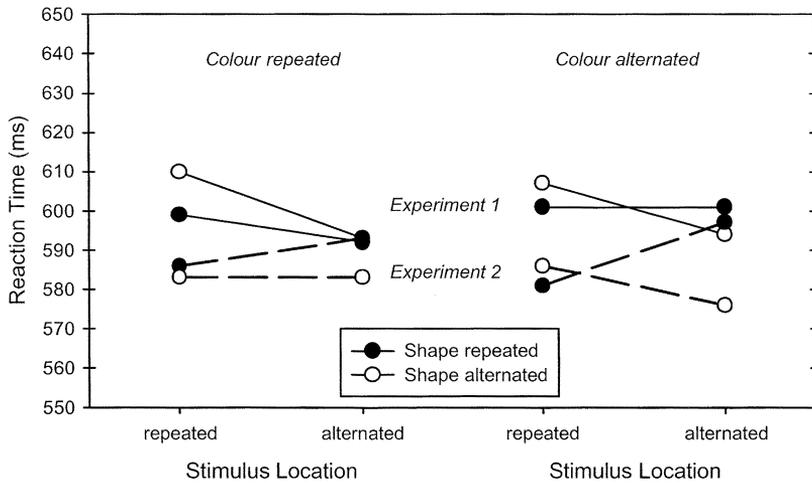


Figure 5. Reaction times in Experiments 1 (straight lines) and 2 (broken lines), as a function of the repetition vs. alternation of stimulus location, stimulus shape, and stimulus colour.

shortest SOA only. Moreover, the pattern of the interaction at the 1100 ms SOA was more or less opposite of that obtained for RTs, showing worse performance for shape and location repeated (11.5%) than for both alternated (8.9%) and shape-only (8.4%) or location-only repetitions (8.9%). Although this might indicate a speed–accuracy trade-off, we note that such an inversion is not only uncommon in experiments of this sort (e.g., Dutzi & Hommel, 2003; Hommel, 1998, 2003) but also runs counter the findings from the other SOAs and from Experiment 1—where RT crossover patterns were accompanied by either null effects or comparable effects in error rates.

The third cluster involves interactions between *colour* and *location*. Evidence of such interactions was only obtained in Experiment 1, where errors produced a two-way interaction and RTs a three-way interaction including attention. As shown in Figure 6, the patterns underlying these two effects are very similar: Colour repetitions had no impact if S1 was unattended, while attending it produced a crossover interaction of colour and location. Interestingly, this interaction does not show the “integration signature” of worse performance with partial matches but, on the contrary, better performance for colour-only or location-only repetitions than for the both-repeated or both-alternated conditions.

The fourth cluster involves interactions between *shape*, *colour*, and *location*—all three stimulus features. Such interactions occurred only in Experiment 2, where we obtained a three-way interaction in RTs and a five-way interaction involving attention and SOA in PEs. As Figure 5 indicates, the three-way interaction was due to a decrease of the shape-by-location interaction effect if

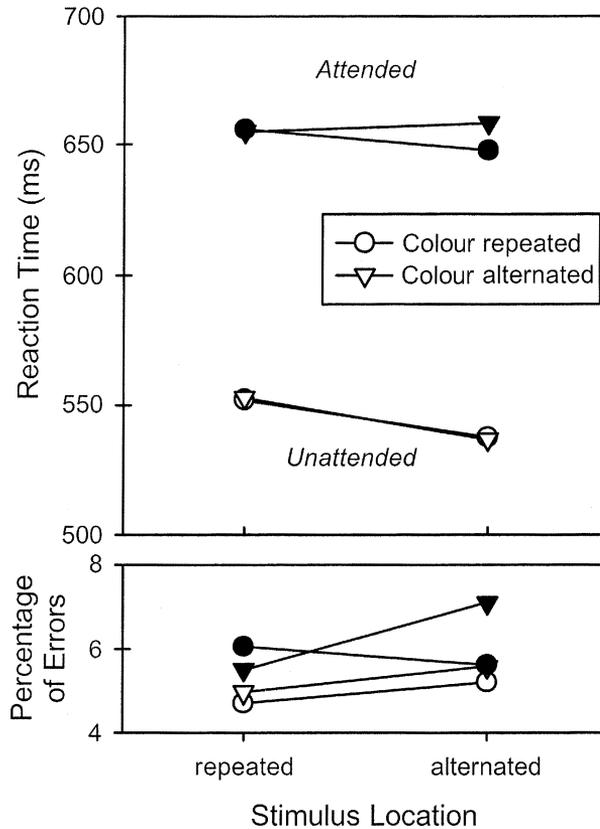


Figure 6. Reaction times and percentage of errors in Experiment 1, as a function of the repetition vs. alternation of stimulus location and stimulus colour, and attention (S1 unattended vs. attended, white and black symbols, respectively).

colour was repeated. To figure out the effect underlying the five-way interaction we ran separate ANOVAs for all combinations of Attention and SOA on the error data from Experiment 2. The outcomes indicated that the three stimulus features interacted only in the 2100 ms SOA cell of the unattended condition. That interaction corresponds to what we see in RTs: Fewer signs of a disadvantage for shape-only or location-only repetitions over both-repeated and both-alternated if colour is repeated (6.8%, 6.2% vs. 8.3%, and 9.0%, respectively) than if colour is alternated (6.8%, 7.3% vs. 5.2%, and 6.6%, respectively).

To summarize, we find evidence of several interactions between stimulus features. From a theoretical point of view, a number of aspects of these findings are of relevance. First, most interactions are bilateral, hence, involve only two of

the three manipulated stimulus features. Second, even the few hints towards an interaction of all three features do not suggest that complete integration took place. If it would have, repeating one more feature should have increased the impact of the other features; yet, the interaction of shape and location decreased if colour was repeated (see Figure 5). Third, there was no support of the idea that integrated feature compounds are addressed by location. If they were, the impact of feature repetitions and their interactions should have increased if, or even be restricted to situations where stimulus location is repeated; yet, a look at Figure 5 confirms that location repetitions did in no way boost the interactions between colour and shape repetition. Fourth, some two-way interactions between features seem to be more reliable and replicable than others. In particular, interactions between shape and location seem to belong to the more reliable effects while the two interactions involving colour seem to be less reliable. Interestingly, colour effects tended to come and go together, hence, all occurred in one but not the other experiment. Finally, there was no evidence of any strong impact of attention or SOA on the interactions involving shape, the nominally task-relevant stimulus feature, and even the remaining interactions did not suggest any strong dependency on SOA.

Stimulus–response-integration effects. The effects falling into our last category all involve response repetition and, therefore, all come from Experiment 2. Let us first turn to interactions involving repetitions of the response and one stimulus feature. Figure 7 provides an overview of the two-way interactions in RTs as a function of attention. It is obvious that all three stimulus features interact with the response, and that they do so as expected: Repeating a response produces better performance than alternation, but only if the respective stimulus feature (shape, colour, or location) is also repeated. If it is not, the repetition effect turns into an alternation benefit.

Some of these interactions were modified by attention and SOA. As evident from Figure 7, the interactions between *shape* and *response* and between *location* and *response* are substantial (and reliable) under both attention conditions but somewhat more pronounced if S1 is attended. SOA also matters, which can be seen in Figure 8. Both the interactions between shape and response and between location and response are most pronounced at the shortest SOA and then decrease as SOA increases. However, even at the longest SOA they are still highly reliable. The shape-by-response interaction in PEs is further modified by a four-way interaction involving attention and SOA, indicating that the decrease of the shape-by-response interaction across SOAs is more pronounced in the S1-unattended than in the attended condition.

Let us now turn to interactions involving the response and two stimulus features. There were three clusters of interactions of that sort. First, *shape*, *colour*, and *response* produced a three-way interaction in RTs, which was modified by a four-way interaction with attention. As shown in Figure 9, the

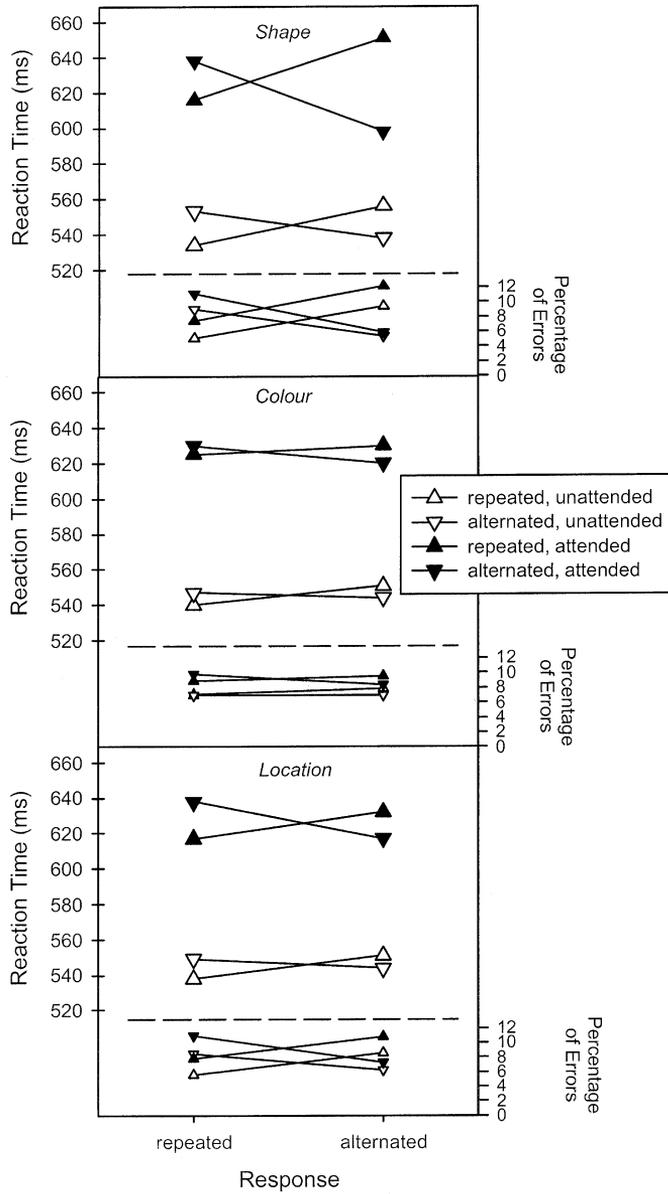


Figure 7. Reaction times and percentage of errors in Experiment 2 for the repetition vs. alternation of stimulus shape (top panel), stimulus location (middle panel), and stimulus colour (bottom panel), as a function of response repetition and attention (S1 unattended vs. attended, white and black symbols, respectively).

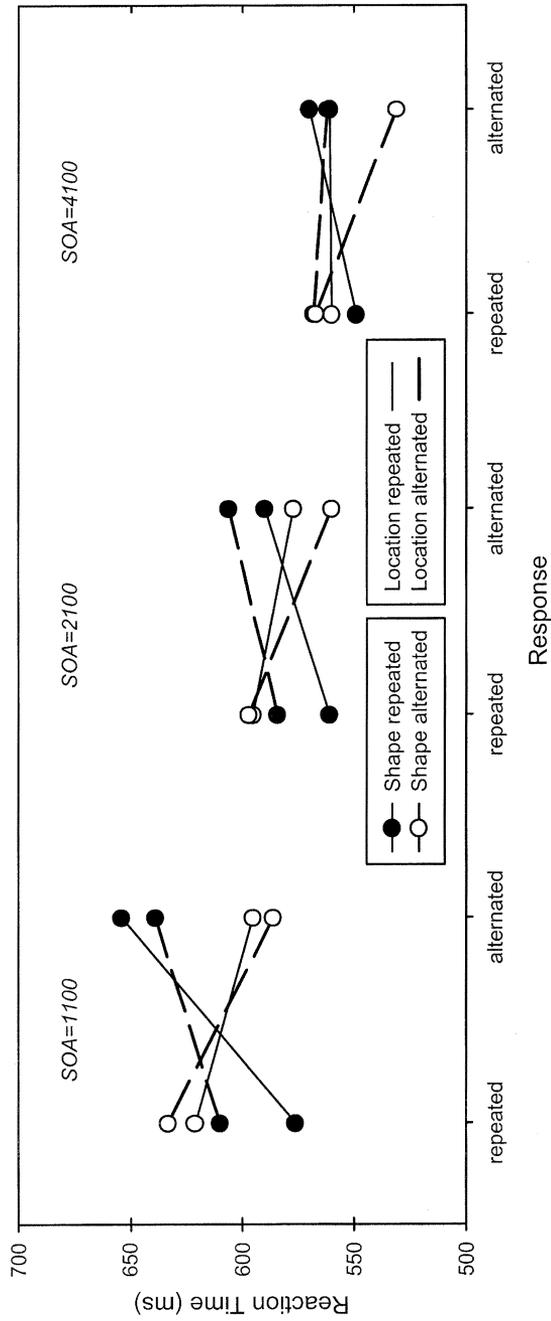


Figure 8. Reaction times in Experiment 2 for the repetition vs. alternation of stimulus shape (black vs. white symbols) and stimulus location (straight vs. broken lines), as a function of response repetition and stimulus-onset asynchrony (SOA, in ms).

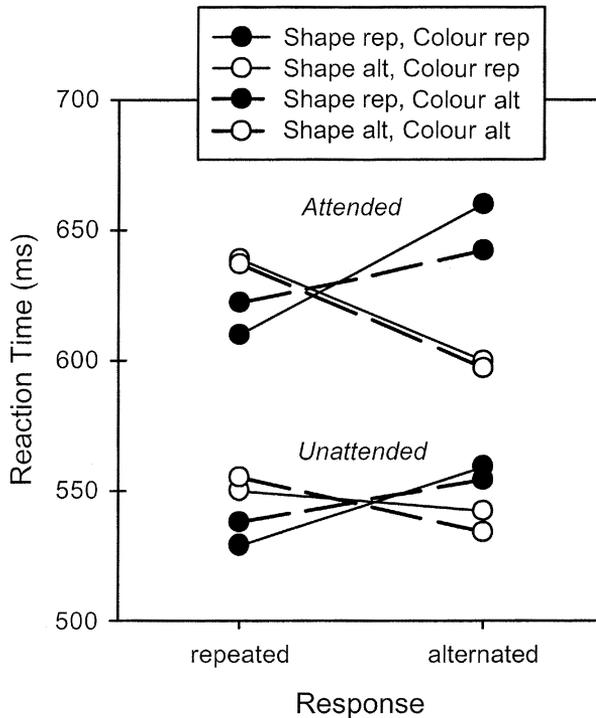


Figure 9. Reaction times in Experiment 2 for the repetition vs. alternation of stimulus shape (black vs. white symbols) and stimulus colour (straight vs. broken lines), as a function of response repetition and attention.

interaction between shape and response was slightly bigger if colour was also repeated (compare straight vs. broken lines), and this increase was more pronounced if S1 was attended (i.e., in the top part of the figure). Importantly, however, the shape-by-response interaction was reliable for all four combinations of colour repetition and attention.

Second, there was a three-way interaction of *shape*, *location*, and *response* in error rates, which was modified by attention and accompanied by a four-way interaction of shape, location, response, and SOA in RTs. The RT effect is shown in Figure 8. As confirmed by separate ANOVAs, shape, location, and response interact at the shortest SOA only, where the shape-by-response interaction is increased if location is repeated. The error-related effects are presented in Figure 10. They mirror the impact of colour on the shape-by-response in showing that repeating location increases the interaction between shape and response (compare straight vs. broken lines), and that it does more so if S1 is attended.

Third, we obtained a four-way interaction of *colour*, *location*, and *response* with attention in error rates. Figure 11 shows that part of this effect is due to that

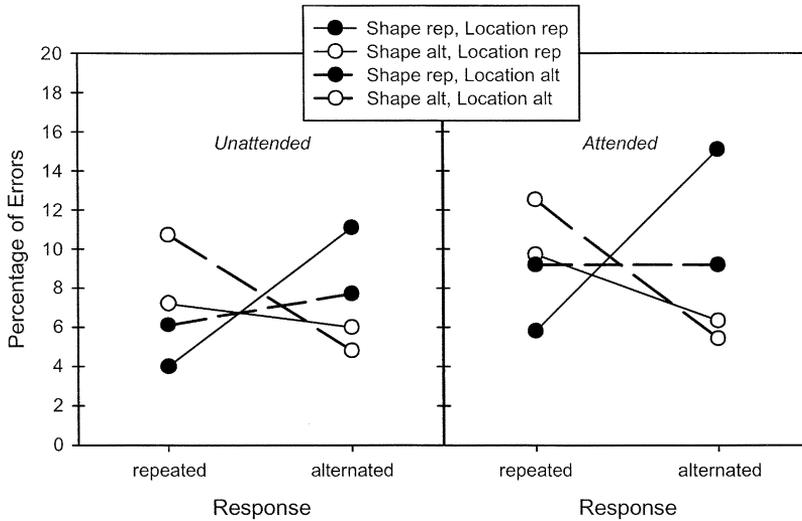


Figure 10. Percentage of errors in Experiment 2 for the repetition vs. alternation of stimulus shape (black vs. white symbols) and stimulus location (straight vs. broken lines), as a function of response repetition and attention.

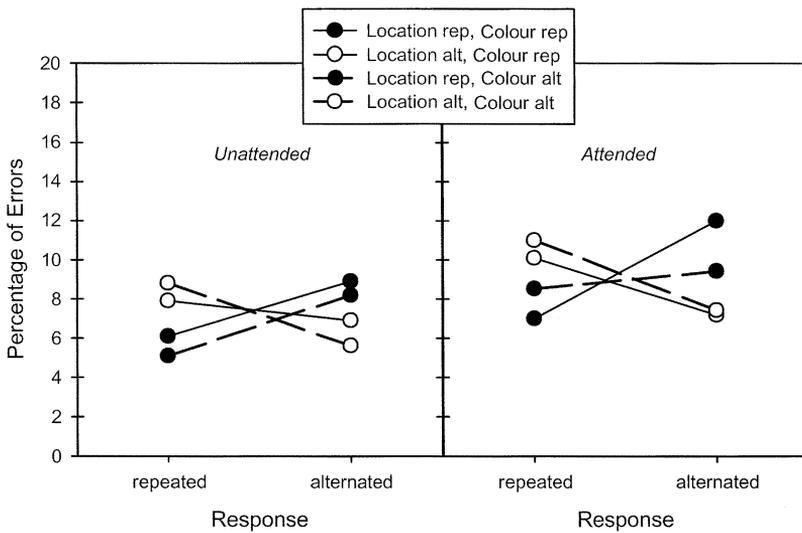


Figure 11. Percentage of errors in Experiment 2 for the repetition vs. alternation of stimulus location (black vs. white symbols) and stimulus colour (straight vs. broken lines), as a function of response repetition and attention.

colour repetitions increase the location-by-response interaction if S1 is attended (see right panel). In contrast, in the unattended condition the location-by-response interaction is less pronounced for colour repetitions than alternations.

To summarize, we find evidence that all three stimulus features were able to modify the effect of response repetitions or, depending on how one looks at it, that response repetitions modified the impact of repetitions of stimulus shape, colour, and location. The task-irrelevant colour dimension seemed to play a minor, more modifying role: The interaction between colour and response repetition was the by far least pronounced but a repeating colour in several cases increased the interactions of other stimulus features with the response. Shape and location repetitions interacted more strongly with the response, and these interactions were further boosted by attending to S1. Increased attention to S1 increased a number of interactions but there was no evidence that endogenous attention was necessary for an interaction to occur. Also, SOA had no dramatic effects but its impact was more obvious than in the interactions between stimulus features.

Conclusions

The two experiments of this study aimed at addressing three questions regarding the integration of stimulus and response features: How complete is feature integration? Are feature bindings addressed by location? and How are feature priming and feature integration related? In particular, we were interested to see whether the completeness of integration, the integration of location codes, and the role of priming and integration would change over time—i.e., SOA—and depend on the amount of attention spend on the to-be-integrated stimulus. All in all, it is fair to say that the impact of attention and time was rather limited. But let us discuss the three guiding questions in turn.

How complete is feature integration? Importantly, we were able to replicate the main finding of Hommel (1998), namely, that the impact of repeating a stimulus feature depends on whether or not other stimulus features and/or the response are repeated as well. Of the binary interactions we obtained, those involving stimulus shape, stimulus location, and response were particularly pronounced and reliable. On the basis of our present data, we are unable to exclude that this reflects characteristics of these particular stimulus and response dimensions or modalities. However, there are two observations that speak against such an interpretation. One is that Hommel (1998) found the predominance of shape–response interactions to turn into a predominance of colour–response interactions when colour was made the relevant dimension for the S2–R2 task. Another is that Hommel (2003) was able to eliminate interactions involving stimulus location by using nonspatial responses (single vs. double key presses). In view of these findings we interpret the present

preponderance of stimulus shape, stimulus location, and response as reflecting the impact of (RT-)task relevance. Indeed, shape was relevant for the RT task by virtue of signalling R2, responses were relevant by definition of the task, and location was—more indirectly—made relevant by defining the responses in terms of spatial location. From this perspective, the likelihood for a stimulus or response feature to enter binary interactions was determined by task relevance of the dimension on which the feature is defined (Hommel, 2003).

We speculated that integration may begin with creating binary bindings (that dominated in the studies of Hommel, 1998, 2003), which then over time enter a more comprehensive object or event file, and this process may be boosted either in terms of time or outcome by attending S1. If so, we would have expected interactions among stimulus and/or response features to increase in order as SOA increases, especially in the attended condition. However, Experiment 1 did not produce any evidence of a more than two-way interaction between stimulus features in RTs or errors, be it in the form of a three-way interaction or a higher order interaction involving attention or SOA. Experiment 2 yielded some more evidence of this sort.

First, the three stimulus features were involved in a three-way interaction and in a five-way interaction with attention and SOA. If one considers the increasing completeness of feature integration to make the final product more specific (by virtue of describing the filed object or event more comprehensively), its impact on behaviour should become increasingly selective. Ideally, and ignoring any possible main effect of feature repetition, one would thus expect that complete integration makes complete repetition special in producing considerably better performance than any other combination of repetitions and alternations. However, a look at Figure 5 shows that this is not what happens, which we think speaks against an interpretation in terms of complete integration. Moreover, such an interpretation would be difficult bring in line with the observation that the five-way interaction locates the main action at the middle SOA of the unattended condition. A possible way to reconcile the idea of increasing integration with the three-way pattern in Figure 5 (though not as smoothly with the five-way interaction) would be to think of it as showing that the more stimulus features are repeated the less is the impact of each individual feature. That is, repetitions of feature conjunctions may be able to outweigh the impact of partial mismatches of other conjunctions to some extent, which does suggest some sort of higher order integration. But even then it would not be obvious why integration should have been less pronounced in Experiment 1, where we could not find any sign of a higher order interaction. Whichever interpretation one prefers it seems clear, however, that our findings do not suggest that integration comprises a transition from local, binary bindings to one global file where all information converges. Thus, object files seem to consist of a loosely connected, distributed network of bindings rather than one single superstructure (Hommel, 1998, 2003).

Second, there were a number of higher order interactions involving one stimulus feature and the response and two stimulus features and the response. In fact, all three binary combinations of stimulus features interacted with response, and all these interactions were modified by attention to S1. The general pattern of the resulting four-way interactions was rather consistent: Repeating one more stimulus feature increases the interaction between another stimulus feature and the response, but only or mainly in the S1-attended condition. A look at Figures 8, 10, and 11 reveals a hint to the possible mechanism underlying this pattern. In all cases the major contribution to the interaction comes from the condition where S2 shares most features with S1 (e.g., shape and location repeated in Figure 10) but a response alternation is required. It is as if a stimulus that is very similar to the previous one induces a tendency to repeat the response, which in case of response alternation needs to be inhibited. Such a tendency has already been considered to account for response repetition benefits in binary-choice tasks. For instance, Bertelson (1963) claimed that people check new stimuli against representations of previous ones and immediately proceed to repeating the last response if the two stimuli match. It is reasonable to assume that this matching strategy is more likely to be applied if the compared stimuli are both attended, which indeed is the standard condition in studies on response repetition benefits. If so, our finding of attentional modulations of higher level stimulus–response interactions may not have much to do with feature integration processes but, rather, reflect the fact that Bertelson’s response selection strategy was restricted to attentional conditions. Such an interpretation would also fit with the four-way interaction depicted in Figure 8: While the shortest SOA shows a pattern indicative of the Bertelson strategy (i.e., slowest performance if a response alternation was required in the face of shape and location repetition) the longer SOAs do not. Indeed, applying the matching strategy presupposes an active memory trace of the previous response, which according to the interaction of SOA and response repetition was effective at the shortest SOA only.

Thus, taken altogether, we find no strong evidence that having more time available and/or investing more attentional resources to process an event creates a single cognitive structure where information about all features of the event converges. Evidence is also sparse with respect to the less ambitious version of this question whether attention and/or time increase integration, that is, whether the resulting structure becomes more complex. There are some hints to higher order interactions among stimulus-related effects and to higher order interactions between multiple stimulus effects and response repetition, but the patterns of these interactions do not seem to fit the idea of (more) complete feature integration. In particular, the resulting representational structures do not get more specific or selective as a function of attention or time. That is, not all features of a given perception–action event are integrated with each other. What gets integrated seems to be determined by task relevance or, more precisely, by

whether the given feature varies on a dimension that in the present task is explicitly or implicitly defined as relevant. In the present RT part of the task, this applied to shape, which was relevant for S2, and to location, which was relevant for the responses. However, it is likely that task relevance is only one factor that affects integration. Stimulus features that are sufficiently salient, such as tones, may enter integration processes even if they are not relevant at all (Dutzi & Hommel, 2003).

Are feature bindings addressed by location? According to Kahneman et al. (1992), object files can only be accessed via spatial information, so that information about the relative or absolute location of its object is an essential ingredient of every object file. If so, feature-binding effects could only be obtained if stimulus location is repeated, which implies that interactions between feature-related repetition effects should always be modified by a higher order interaction with stimulus location. Our results not only replicate previous demonstrations that this prediction is incorrect (Hommel, 1998, 2003; see also Gordon & Irwin, 1996; Henderson, 1994; Henderson & Anes, 1994), they also show that the picture these demonstrations suggest does not change much if attention and time come into play. In particular, a whole number of reliable interactions between effects of stimulus features and between effects of stimulus and response features were obtained in the absence of stimulus repetition, and even though attending S1 increased some of these effects their existence did not depend on attention or time.

Thus, on the one hand, our findings do not support Kahneman et al.'s (1992) claim that object files are exclusively addressed by location. Rather, it seems that any match counts, which implies that a given stimulus or action event activates or primes all feature compounds that include at least one feature code of a matching value. This view fits nicely with the developmental evidence mentioned above (Leslie & Kaldy, 2001; Leslie et al., 1998) and with the assumption that episodic event representations can be addressed by a match with any feature code they include (Hommel, 1998; Hommel, Müsseler, Aschersleben & Prinz, 2001b; Leslie et al., 1998). On the other hand, however, our findings should not be taken to rule out all possible roles of stimulus location for feature integration. It may well be that integration is under spatial control, as several authors have claimed (e.g., Treisman, 1988; van der Heijden, 1992; Wolfe, 1994). That is, the criterion for sampling information into the same event representation may well be defined in terms of the location the information is coming from, in addition to possible temporal constraints (Hommel & Akyürek, 2003). And yet, this need not necessarily imply that location is coded in the emerging representation.

How are feature priming and feature integration related? With regard to the priming of single features, previous studies yielded a rather inconsistent

picture: Some did find reliable effects (Gordon & Irwin, 1996; Henderson, 1994), while others did not (Hommel, 1998; Kahneman et al., 1992). We hypothesized that this apparent inconsistency might be due to the different SOA ranges used in these studies and thought that priming may show up at very short SOAs only. Indeed, Figure 4 and the corresponding analyses clearly indicate that most priming is restricted to the shortest SOA used here, i.e., 200 ms. If we assume that the amount of priming reflects the degree of activation of the respective feature code, this observation suggests that activation and integration do not necessarily go together. Thus, on the one hand, it is likely that what gets integrated is what is currently activated, which implies that the activation of a feature code precedes, and may even be the criterion for its integration (Hommel et al., 2001b; Hommel, Müsseler, Aschersleben & Prinz, 2001a). Once integration has taken place, however, activation is no longer necessary to impact processing (Hommel, 2002). For a concrete example, the temporal overlap of activation in the codes <vertical> and <bottom> creates a temporary link between them, as shown in Figure 1. Without activating these codes the link would not have been created, so that activation necessarily precedes integration. Once the link is established, however, activation is no longer needed: When <vertical> is activated again it will spread activation to <bottom>, and vice versa.

A rather surprising outcome of our study is the impact of attention—or the lack of it. On the one hand, explicitly attending to S1 and storing its features had a pronounced effect on performance, as revealed by a look at Figure 3. This assures us that the attentional part of our manipulation worked. On the other hand, however, the performance deficits produced by this manipulation are likely to reflect the consolidation of object information into working memory (Jolicœur & Dell'Acqua, 1998; Jolicœur et al., 2002), a process that is assumed to share capacity with and therefore delay response selection (of R2 in our case). Consolidation into working memory, though, has been likened to feature integration (Luck & Vogel, 1997; Vogel et al., 2001), which one would assume to boost interactions between feature-related effects. Accordingly, one might have expected a stronger impact of our memory probe task on the interactions between feature repetition effects. A tenable account for this might be to assume that our subjects used verbal coding strategies to retain the features of S1—an account that is also suggested by the high asymptote in the attended condition (see above). If so, it was verbal, not visual feature codes that were consolidated, which again is unlikely to provide any particular support for the type of feature integration that we believe to underlie the observed interactions between feature repetition effects. It may therefore well be that taking measures to exclude verbal strategies would allow for a greater impact of the probe task on feature interactions. At any rate, however, it seems clear that these interactions do not require active consolidation to occur.

Further theoretical implications

Taken altogether, the present study confirms that the mere cooccurrence of stimulus features, and of stimuli and responses, is sufficient to induce bindings between their codes. These bindings emerge rather quickly—i.e., within the first hundreds of milliseconds—and remain intact for at least 4 seconds. Which features are bound depends to a large degree on the direct or indirect task relevance of their dimension. That is, feature integration within perception and across perception and action occurs spontaneously, but its outcome is codetermined by the current action goal and the attentional set implemented to achieve it. Let us conclude by pointing out some more general implications our findings, especially with regard to the processing and representation of events in and across perception and action.

It is fair to say that the discussion of possible roles of binding processes and the neural codes that might mediate them is still controversial, if not fiercely: Some authors have emphasized the need of integration processes in distributed representational systems like the human brain and argued that the synchronization of cell populations might play a major role in binding features belonging to the same event (e.g., Singer, 1994; Treisman, 1996), while others have questioned the very necessity of feature binding (e.g., Cisek & Turgeon, 1999; van der Heijden, 1995) and/or the involvement of neural synchronization in it (e.g., Jellema & Perrett, 2002; van der Velde & de Kamps, 2002). In this and previous studies we have taken a pragmatic, empirical stance and looked whether or under which circumstances evidence for binding can be found at all. As discussed, there is increasingly strong and converging evidence that binding does take place and that it does affect performance, and the present study extends this evidence by showing that it does so at least for a couple of seconds and even if the bound features need not be processed very deeply. Given the ongoing controversy it seems particularly important, however, to point out what our findings do *not* show.

First, there is no evidence that visual features can affect behaviour only if, or only after they have been integrated—as one would have expected on the basis of Kahneman et al. (1992; cf. Phaf, van der Heijden, & Hudson, 1990). If anything, our observations suggest the opposite: Main effects of feature repetitions—which represent the impact of a feature code independent from, or on top of any binding it may be involved in—were restricted to very short SOAs, whereas the interactions that we attribute to feature integration were found across the whole SOA range. As pointed out above, this suggests the existence of at least two functionally separable representations of an event: A map or system in which the features of an event are coded by (rather briefly) activating their respective feature codes and a network of links connecting the codes that are coactivated within a particular integration window (Hommel et al., 2001b; cf. Styles & Allport, 1986). It is tempting to relate the former to the increase of

firing rates of cell populations within feature-specific representational maps and the latter to the synchronization of the firing patterns of cell populations across representational maps (as suggested by Singer, 1994; Treisman, 1996; and others), but our data do not directly speak to the issue of how activation and binding of feature codes is neurally implemented.

Second, and relatedly, demonstrating aftereffects of feature integration does not necessarily rule out the possibility that the integrated features were encoded and processed independently, as predicted by parallel models of feature processing (e.g., Bundesen, 1990) and observed at least under some conditions (Bundesen, Kyllingsbæk & Larsen, 2003). Obviously, a feature code can only be integrated and retrieved if the respective feature has been successfully encoded, and there is no reason why the likelihood of encoding one member of an integrated event representation should depend on the likelihood of encoding another member of the same representation. However, once two or more feature codes are encoded and bound, they tend to prime each other and, thus, act as a functional unit—an event file. This observation does not challenge the basic assumptions most attentional models rely on, but it makes these models incomplete with respect to the outcome of feature integration processes (see Logan, 2002, for an attempt to overcome this shortcoming).

Third, our failure to find an effect of our attentional manipulation shows that binding does not require an explicit intention to integrate information about an event, nor does it presuppose that its outcome is of any use for the task at hand. Note that this does not demonstrate that integration is independent from the attentional set or the availability of attentional resources. To the contrary, the important role of set is obvious from the observation that features are integrated only if they are directly or indirectly related to the task (Hommel, 1998, 2003). That is, feature integration seems to be controlled by the task goal, which may be maintained in working memory and provide top-down support for information related to task-relevant feature dimensions (Desimone & Duncan, 1995; Pratt & Hommel, 2003). Once this support is provided integration seems to proceed automatically, however. How automatically it proceeds may well depend on the concrete visual situation, such as the presence and number of alternative targets and distractors. Whereas no explicit intention to integrate was necessary under the Spartan conditions in our experimental set-up—with only one, salient stimulus appearing in a rather wide time window—it seems likely that more complex visual situations, such as the multielement displays used by Kahneman et al. (1992), make selection and integration goals more relevant.

To conclude, irrespective of the eventual outcome of the “binding-problem” debate, the present study provides converging evidence that feature binding both within visual perception and across perception and action is a real empirical phenomenon that calls for theoretical consideration and further investigation.

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