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Feature integration across perception and action: event files affect response choice

Abstract Five experiments investigated the spontaneous integration of stimulus and response features. Participants performed simple, prepared responses (R1) to the mere presence of Go signals (S1) before carrying out another, freely chosen response (R2) to another stimulus (S2), the main question being whether the likelihood of repeating a response depends on whether or not the stimulus, or some of its features, are repeated. Indeed, participants were more likely to repeat the previous response if stimulus form or color was repeated than if it was alternated. The same was true for stimulus location, but only if location was made task-relevant, whether by defining the response set in terms of location, by requiring the report of S2 location, or by having S1 to be selected against a distractor. These findings suggest that task-relevant stimulus and response features are spontaneously integrated into independent, local event files, each linking one stimulus to one response feature. Upon reactivation of one member of the binary link activation is spread to the other, thereby increasing the likelihood to repeat a response if one or more stimulus features are repeated. These findings support the idea that both perceptual events and action plans are cognitively represented in terms of their features, and that feature-integration processes cross borders between perception and action.

Introduction

The things we perceive and the actions we perform are characterized by their features. We eat cookies that are round, brown, and sweet, drink coffee that is fluid, black, and bitter, we move our head slowly to the right,

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and our left hand quickly towards a goal in front of us. Brains of humans and other primates represent these features in a distributed fashion, that is, they code different features of a given event in different, in part even differently organized cortical areas. This is particularly true for visual information, which activates cells throughout the whole visual cortex coding a given event's form, color, orientation, motion, and more (e.g., DeYoe & Van Essen, 1988; Ungerleider & Haxby, 1994). But it also holds for the codes involved in planning the features of an intentional action, as indicated by the demonstration of separable neural representations for movement direction (Alexander & Crutcher, 1990; Georgopoulos, 1990), force (Kalaska & Hyde, 1985), and distance (Riehle & Requin, 1989) in monkeys and of duration (Vidal, Bonnet & Macar, 1991), force (Bonnet & MacKay, 1989; Kutas & Donchin, 1980), and to-be-used hand (Osman, Bashore, Coles, Donchin & Meyer, 1992) in humans.

The demonstration of distributed, feature-based representation on the brain level does not necessarily indicate or require a comparable format of representation on functionally defined, cognitive levels. However, there is increasing evidence that even functionally defined cognitive representations can be characterized as assemblies of feature-related codes (Barsalou, 1999; Damasio, 1989; Hommel, Müsseler, Aschersleben, & Prinz, 2001). For instance, the speed of both detecting a visual stimulus and planning an action varies strongly with the number of features the stimulus or action is defined by (see overviews in Wolfe, 1998; Rosenbaum, 1987, respectively), and failures in both perception and action planning often result in feature-based errors (e.g., Treisman & Gelade, 1980; Rosenbaum, Weber, Hazelett, & Hindorff, 1986, respectively). As several authors have pointed out, the existence of distributed representations poses the question of how the distributed codes of a given event are integrated in perception (Treisman, 1996) and action planning (Stoet & Hommel, 1999; Wickens, Hyland, & Anson, 1994).

Integration of stimulus and response features

Feature integration is a common theme in visual perception but much less topical in the area of action planning (Stoet & Hommel, 1999, 2002; Wickens et al., 1994), and even less with respect to the relation between perception and action planning. However, considering that higher organisms acquire associations between stimuli and responses, the assumption that stimuli as well as responses are represented in terms of distributed feature codes does raise the question of how and according to which principles these features are integrated. One means to investigate this process has been employed in a study of Hommel (1998). In this study, participants performed a reaction-time (RT) task, in which each trial comprised three stimuli and two responses. First, a response cue was presented to indicate whether the first response (R1) should be a left-hand or a right-hand keypress. Participants were to prepare the cued keypress and to carry it out in response to a trigger stimulus (S1) that appeared a few seconds later. A second later another stimulus (S2) appeared, and participants were instructed to respond to its form (or, in another experiment, to its color) by pressing the left or right key (R2). Hence, participants performed sequences of a simple RT task followed by a binary-choice RT task. What varied was the identity of R1 and R2 and the form, color, and location of S1 and S2.

As one might expect, all sorts of repetition effects were obtained for both stimuli and responses. However, more interesting for our purposes are the interactions between these effects, especially those involving stimulus and response features. First, it turned out that repeating the task-relevant stimulus feature (i.e., the S2 feature that signaled R2) sped up R2 but only if R2 was also a repetition of R1; if not, alternations of that stimulus feature yielded better performance. As an example, assume form was task-relevant by virtue of signaling R2. In that case response repetitions ($R2_{location} = R1_{location}$) were faster and more accurate if form was also repeated ($S2_{form} = S1_{form}$) than if form alternated ($S2_{form} \neq S1_{form}$). In contrast, response alternations ($R2_{location} \neq R1_{location}$) were faster and more accurate if form alternated ($S2_{form} \neq S1_{form}$) than if form was repeated ($S2_{form} = S1_{form}$). This seems to indicate that the relevant stimulus and response features are integrated into what Hommel (1998, 2004) called "event files". The basic idea is that stimulus and/or response features that are activated (through perception of the stimulus and/or selection of the response) sufficiently close in time are temporarily bound together and act as a unit (cf., Milliken & Lupiáñez, 2005). If one or more members of a given event file is reactivated the whole file will be reactivated, that is, activating the code of one member (a stimulus or response feature included in the file) spreads to all the other members. This creates coding conflict (in perception or response selection) if the overlap between the filed event and the new event is only partial, hence if some features are repeated but others are not. In case of

the Hommel (1998) study, perceiving an X (S1) while carrying out a left-hand response (R1) would create a binding of the X and the LEFT code. This would not interfere with either recreating the same binding (X–LEFT) or creating another, nonoverlapping binding (O–RIGHT), but would impair creating a binding that shares some but not all feature codes (X–RIGHT or O–LEFT)—see Hommel (2004) for further considerations regarding the underlying mechanisms.

A second interesting result of the Hommel (1998) study was that stimulus location interacted with the response independent from the relevant stimulus dimension and even though stimulus location itself was nominally not relevant at all. That is, response repetitions ($R2_{location} = R1_{location}$) were faster and more accurate if location was repeated ($S2_{location} = S1_{location}$) rather than alternated ($S2_{location} \neq S1_{location}$), while the opposite was true for response alternations ($R2_{location} \neq R1_{location}$). One possibility is that this observation reflects the special role location information is attributed in the process of feature integration. For instance, Treisman (1988) and Wolfe (1994) have claimed that the integration of visual features is mediated by, and channeled through a master map of locations, which might lead to the obligatory inclusion of spatial information into emerging object and event bindings. Indeed, Kahneman, Treisman, and Gibbs (1992) assumed that if representations of moving objects are updated their bindings are addressed with reference to the object's previous location, which implies that location information has become part of the binding. In fact, Hommel (2002) demonstrated that objects retrieved from working memory produce a spatial compatibility effect (i.e., facilitate responses that spatially correspond with the remembered object), suggesting that their representations include location information. However, the findings of Hommel (1998) may also have to do with the fact that his task involved spatial responses. Employing a spatially defined response set may in some sense introduce location as a task-relevant feature, so that the location-related findings may be taken as a demonstration that task-relevant stimulus and response features get integrated (Hommel, Pösse, & Waszak, 2000; Mayr & Bryck, 2005).

It is important to note that, and in which way, these findings go beyond previous demonstrations of stimulus- and/or response-repetitions effects. Sequential effects are known since the work of Hyman (1953) and Bertelson (1961), who observed that RTs are faster if a particular stimulus–response combination is repeated than if it is not (for overviews, see Kirby, 1980; Kornblum, 1973). At least two mechanisms have been claimed to be at work in producing such effects: the presumably automatic facilitation of response repetitions, which dominates at short inter-response intervals (IRIs), and presumably more strategic expectations favoring response alternations, which dominate at longer IRIs (Bertelson, 1961; Soetens, Boer, & Hueting, 1985). Existing accounts can explain why a complete repetition

Fig. 1 Sequence of events in Experiment 1A
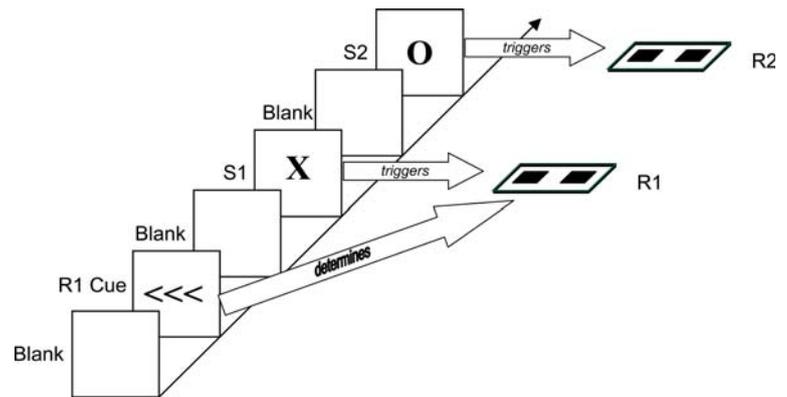
(i.e., stimulus *and* response feature) yields better performance than a partial repetition (i.e., stimulus *or* response feature). However, why a complete alternation should produce better performance than a partial repetition they are unable to explain. Although this critique does not invalidate their account of repetition main effects of stimuli and responses, it does suggest that these main effects reflect different mechanisms than the interactions observed in the Hommel (1998) study. Indeed, there is evidence that repetition main effects on the one hand and interactions between them on the other follow separable time courses, with the former being transient and restricted to very short stimulus onset asynchronies (up to 300–500 ms) and the latter being more stable and setting in later (300–4,000 ms or longer; Hommel & Colzato, 2004). So, what counts for the present study are not repetition effects as such, which we already know to exist, but the interactions between these effects. It is only dependencies among repetition effects that point to the possible integration of stimulus and response codes.

Aims of study

The main purpose underlying the present series of experiments was to search for independent, but hopefully converging, evidence for the existence of event files, i.e., bindings between stimulus and response features. Instead of RTs, the measure of interest in the Hommel (1998) study, the present study focused on the likelihood to choose particular responses. In other words, here it was not the speed but the outcome of response selection that mattered. As we will see below, using response choice allows us to address some questions that would be very difficult to deal with on the basis of the original design introduced by Hommel (1998).

Indeed, even though Hommel's (1998) observations can be taken as evidence that stimulus and response features are integrated into event files, a couple of open questions remain. First, the particular design used to demonstrate interactions between repetition effects may raise some objections. Consider the sequence of simple- and choice-RT task as described above. The second, choice task is only to measure the after-effects of the

hypothetical binding of S1 and R1 features. Yet, it requires some mapping that relates R2 to S2 features, such as "press a left/right key in response to red/green". Given the necessary feature overlap between S1 and S2, and between R1 and R2, relating S2 and R2 may affect the processing of S1 and R1. Assume, for instance, R2 were assigned to S2 in terms of S2 color as in the example, that is, left and right keypresses to the colors red and green, respectively. In case of both a complete repetition or complete alternation of stimulus color and response the relations between S1 and R1 correspond to the S2–R2 mapping, while they do not in case of partial repetitions. Accordingly, one may argue that the observed disadvantage of partial repetitions does not reflect the binding of S1 and R1 features, or its conflict with S2 and R2 processing, but some after-effects arising from the confusion created by the mismatching S–R rule during S1 and R1 processing. To check for that, Hommel (1998) analyzed the RTs for R1, examining whether rule-incongruent S1–R1 pairings were taking more time to perform than congruent pairings. No such effects were obtained, which provides some evidence against a rule-based account. However, one may argue that rule confusion arose only later, perhaps in the process of response evaluation (Gehring, Goss, Coles, Meyer, & Donchin, 1993) and, hence, was not reflected in RTs of R1.

To rule out such later effects one would need to get rid of any particular mapping of particular stimulus and response features in the second, "indicator" task but still obtain some measure of repetition effects and, more importantly, their interactions. This is what I attempted to achieve in the present study. It employs a novel combination of the first part of Hommel's (1998) task—the R1 precue and the following R1 triggered, but not determined, by S1—and a binary free-choice task. The basic structure of the resulting hybrid task is shown in Fig. 1. Participants performed left–right keypressing responses or, in later experiments, single- versus double-keypress responses. The first response R1 was indicated by a cue, and participants were to prepare this R1 and perform it as soon as S1 was presented. Thus, the identity of R1 was not determined by, and therefore did not depend on S1, which only served as a trigger or go signal. Also of importance, none of the manipulated S1

or R1 features were correlated with the other, so that participants could not get any information out of attending the features of S1 or their relation to R1. Nevertheless, on the basis of Hommel's (1998) findings I expected that at least some features of S1 and R1 would be integrated with each other, and that this integration would affect the following response. This second response R2 was triggered by S2, a stimulus that could share or not share features with S1. In a few trials S2 was omitted, in which case participants were not to carry out R2. If S2 would appear, however, they were to perform one of the two possible responses. In principle, they were free to choose among these two alternatives, although a few time and choice restrictions were introduced to counteract at least some of the response strategies such situations are likely to induce.

The rationale behind this task design was to look at stimulus- or binding-related response tendencies more directly. If people can choose between one of the two alternative responses after just having performed one of them, they have the option to repeat that response or go for an alternation. If response choice is not determined by any instructed S–R mapping, on what might it depend? First, and perhaps even foremost, there are the standard effects of stimulus and response repetition we know from the literature. Importantly, these two types of effects are of differing relevance for the question of which response participants are going to select under free choice, and the way they are expected to differ varies with the theoretical background. Assume the sources of stimulus-repetition and response-repetition effects were independent, as claimed only recently by Kornblum and Stevens (2002). If so, repeating the stimulus would be likely to speed up stimulus processing and, hence, advance the time point when response selection begins. This can be expected to reduce RT but the *outcome* of response selection should not be affected. That is, other things being equal, the rate of response repetitions should be the same under stimulus repetition and stimulus alternation. A comparable prediction can be made for response-repetition effects. These effects are likely to show up in both RTs and response choices, so that response-repetition rates may well deviate from chance (with rates $> 50\%$ indicating repetition benefits and rates $< 50\%$ indicating alternation benefits). However, if stimulus and response repetition effects are really independent, one would not expect that the repetition rate depends on whether the stimulus is repeated or not. Predictions from an integration account are different. Clearly, if in the course of S1 presentation and R1 performance stimulus and response features become integrated (Hommel, 1998), repeating the stimulus should increase the tendency to repeat the response as well (because reactivating stimulus-feature codes spread activation to response-feature codes of the same event file), hence, response-repetition rates should be higher under stimulus repetition than alternation.

All hypotheses tested in this study refer exclusively to response decisions or, more precisely, to the rate of response repetitions, but not to RTs. The main reason for this is that decisions under free-choice conditions are unlikely to represent a pure measure of response tendencies (cf., Elsner & Hommel, 2001). Free response choice is known to be rather demanding and, indeed, free-choice RTs have been demonstrated to exceed forced-choice RTs even if the number of response alternatives is the same (Berlyne, 1957). Accordingly, it is natural that participants attempt to make their task easier by following some strategy, such as repeating their choice for blocks of trials or alternating from trial to trial (cf., Tune, 1964). Moreover, these strategies are likely to vary both within and between participants, which makes them notoriously difficult to predict. Even worse, such strategies might interact with stimulus-induced effects, such as the hypothesized stimulus–response integration effect, in unpredictable ways. Assume, for instance, a participant following some strategy already prepared a response that represents a response alternation. If then the stimulus would repeat and induce the hypothesized response-repetition tendency, the strategically prepared and the stimulus-induced response tendencies would compete. Such a competition would end up in favor of the strategic response the sooner the response is started, because this would leave less time for the stimulus-induced response tendency to grow in strength (Hommel, 1996a, b) and vice versa. Accordingly, stimulus-consistent decisions were associated with longer RTs than inconsistent decisions, a pattern that we in fact will see in several experiments of this study. However, participants may also apply more balanced strategies, which makes predictions of RT patterns increasingly speculative and less reliable. Accordingly, I made no attempt to predict RTs and focused on response choices only, apart from some general considerations on RTs presented in the General discussion. However, in all cases RTs are presented, and their analyses are reported, for the interested reader.

To summarize, in contrast to previous studies that focused on quantitative effects of stimulus and response repetitions (i.e., on selection *speed*), and possible integration effects, the present study aimed at producing qualitative effects (i.e., on selection *outcome*). This approach, and the associated task design, has several advantages. First, it measures response tendencies relatively directly, although only on top of other, to-be-expected strategic effects. This will allow us to critically evaluate the stimulus–response binding account of Hommel (1998) and Hommel et al., (2001) against approaches claiming independent contributions from stimulus and response repetition. Second, the absence of any specific stimulus–response mapping rules out any account of the outcome in terms of response-rule congruency or incongruency—a possible objection against the Hommel (1998) study. Third, the absence of particular stimulus–response rules allows us to vary the task relevance of stimulus and response features more freely and independently of each other. In previous studies, some stimulus and response features, and their relations, were always

explicit, defining aspects of the task, which makes it difficult to rule out that their integration was a by-product of the mental set required to perform the speeded response-choice part of the task. Not so in the present study, where the relevance of stimulus features and response features could vary independently of each other.

Experiment 1

The main purpose of the first set of experiments was to establish the experimental paradigm and to see whether reliable effects on response choices can be obtained at all. Of particular interest was whether the tendency to repeat (or alternate) a response depends on whether the stimulus also repeats or not. Accordingly, the dependent measure of interest was the percentage of response repetitions, as a function of stimulus repetition or alternation. In each trial of Experiment 1A, participants carried out two responses. The first was a precued left or right keypress (R1), as indicated in Fig. 1. Participants prepared the response upon precue presentation and carried it out as soon as the first actual stimulus S1 appeared. As in the Hommel (1998) study, S1 only served to trigger R1, so that apart from its onset no feature of S1 was relevant to the task. If R1 was correct S2 appeared, to which participants were instructed to respond with a freely chosen left or right keypress (R2). Thus, S2 also served as a mere trigger, and none of its features was of any relevance. There were four experimental conditions. In the first, stimulus-repetition condition the form of S2 was the same as that of S1, which could be the letter O or X. In the second, stimulus-alternation condition, the alternative letter was presented. If these two conditions were to produce different rates of response repetitions, then this would strengthen the idea that stimulus and response codes are integrated. In contrast, approaches assuming independent sources of stimulus and response repetition effects would not predict different rates of response repetition. In a third condition, S2 was a symbol that could never appear as S1, in this case an equal sign (=). This condition was introduced in an attempt to create a neutral condition, so that effects of stimulus and response repetitions could be evaluated in terms of costs and benefits. As we will see, this attempt did not produce systematic results, so it was dropped from Experiment 2 on. The fourth condition was introduced to work against response-choice strategies, and consisted of a nogo trial in which S2 was omitted. As this meant that no R2 was to be carried out, preparing R2 before S2 presentation would produce useless cognitive costs, which again was thought to discourage participants from doing so (Elsner & Hommel, 2001).

Given the arguments for a special role of location in feature integration (e.g., Treisman, 1988; van der Heijden, 1993), Experiment 1B was conducted to test whether stimulus location would have comparable effects to stimulus form. It was a close replication of Experiment 1A, except that the form manipulation was traded for a location manipulation. Thus, participants carried out R1 and R2 triggered by stimuli that varied in location but not form. To anticipate, it turned out that location yielded effects that were even larger than those of form. To figure out whether this might indeed point to a special role of stimulus location for integration or, rather, reflect the fact that location was made task-relevant by using spatially defined (i.e., left–right) responses, Experiment 1C was conducted. It was a close replication of 1B, except that participants carried out single versus double presses of the same key. Replicating a strong effect of stimulus repetition on response repetition under these conditions would point to a location-special interpretation of the outcome of Experiment 1B, whereas the absence of such an effect would indicate that response-induced task relevance was responsible.

Method

Participants

Forty-four adults (27 female and 17 male, aged 20–38 years) were paid to participate in single sessions of about half an hour. They reported having normal or corrected-to-normal vision and were not familiar with the purpose of the experiment. There were 16, 16, and 12 participated in Experiments 1A, 1B, and 1C, respectively.

Apparatus and stimuli

The experiment was controlled by a Hewlett Packard Vectra QS20 computer, attached to an Eizo 9080i monitor. From a viewing distance of about 60 cm, participants faced a square outline of 1.2×1.2 ° (in Experiment 1A) or three gray adjacent frames, vertically arranged square outlines of 1.2×1.2 ° (in Experiments 1B and 1C). Three kinds of stimuli appeared in each trial: a response cue, S1, and S2..

In Experiment 1A, the response cues were horizontal rows of three white left- or right-pointing arrowheads, indicating a left and right response (R1), respectively; S1 was a green, uppercase X or O, measuring 0.3× 0.4 *deg*; and S2 was either a green X or O, a green equal sign (=), or a blank. In Experiment 1B, the response cues were also arrowheads; S1 was a green filled rectangle of 0.3×0.4 *deg* (ASCII code 219) appearing in the top or bottom frame; and S2 was the same as S1 but could appear in any of the three boxes, or could be omitted. In Experiment 1C, the digits 1 and 2 were used as response cues, signaling single and double keypresses, respectively; S1 and S2 were as in Experiment 1B. In Experiments 1A and 1B, responses were made by pressing the left or right of two board-mounted microswitches with the index finger of the left and right hand, respectively; in Experiment 1C, responses were carried out by pressing a single response key once or twice. A double press

was counted if a second response onset could be registered within 200 ms after onset of the first; otherwise, a single press was counted. This short time window was chosen to make sure that participants preprogrammed both single and double responses alike (cf., Hommel, 1996a).

Procedure and design

In each trial, participants saw three stimuli and made two responses: a fully precued, simple reaction, and a go–no-go reaction of freely chosen identity. The sequence of events in each trial (of Experiment 1A) is illustrated in Fig. 1. After a blank intertrial interval of 2,000 ms, R1 was signaled by the response cue for 1,500 ms, followed by a blank interval that varied randomly between 1,000 and 1,200 ms. Then S1 appeared for 200 ms, followed by a further, randomly determined blank interval of 500–700 ms. Participants were instructed to carry out the precued and prepared R1 as soon as S1 appeared, irrespective of its identity. In particular, it was pointed out that there was no systematic relationship between S1 and R1, or between S1 and S2, so that the form of S1 (in Experiment 1A) or its location (in Experiments 1B and 1C) could safely be ignored. If R1 was incorrect, premature (RT < 50 ms), or not performed within 500 ms, a new trial was started. Otherwise, S2 was presented and stayed on until the end of the trial. Participants were instructed to respond to any actual S2 irrespective of its identity (in Experiment 1A) or location (in Experiments 1B and 1C), but to withhold responding if no S2 (i.e., a blank) was presented (nogo trials). It was emphasized that R2 was to be selected freely and randomly, independently of S2, and that any kind of systematicity should be avoided. However, participants were also encouraged to try using the two possible responses about equally often on average.

After S2 was presented, the program waited until R2 was given but not longer than 2,000 ms. If R1 or R2 was premature or missing, or if R1 was incorrect, an auditory error feedback was given, while the trial was recorded and repeated at some random position in the remainder of the block. A session consisted of 16 blocks, the first being considered as practice. Each block comprised 16 randomly ordered trials, composed of the possible combinations of two R1 alternatives, two S1 alternatives, and four S2 alternatives (X, O, =, and blank in Experiment 1A; top, bottom, or middle box, or blank in Experiments 1B and 1C).

Results

Experiment 1A

R1 was initiated after 291 ms on average and with high accuracy (0.8% choice errors or anticipations, and 5.8%

omissions or late responses). R2 was carried out prematurely in 0.4% and too slowly or, in case of S2 omission, needlessly in 1.2% of the trials. Two dependent measures were calculated from the remaining data: R2 choice, expressed as percent response repetitions, i.e., the rate of trials in which R2 repeated R1, and RT of R2. They were analyzed as a function of stimulus-form repetition, which varied on three levels: form repeated (O → O, X → X), alternated (O → X, X → O), or neutral (O → =, X → =). ANOVAs were used for omnibus analyses and t tests for testing expected differences, the significance criterion being $p < 0.05$ in all cases.

As Fig. 2 (left panel) shows, there was an (however, insignificant) overall tendency to repeat responses, that is, the overall rate of response repetitions was larger than 50%, the chance level. More important, however, the rate of response repetitions varied with stimulus repetition, $F(2,30) = 7.97$, an effect that was due to a greater likelihood of repeating responses if stimulus form was repeated rather than alternated or neutral. The RTs also produced a significant effect, $F(2,30) = 11.64$, due to a slight increase of RTs in the neutral condition.

Experiment 1B

R1 was again initiated quickly (309 ms RT) and rather accurately (0.6% choice errors or anticipations, and 5.3% omissions). R2 was carried out prematurely in 0.2%, while response omissions in go and false alarms in nogo trials accounted for 0.5% of the trials. Overall, responses were more often repeated than alternated, as can be seen in Fig. 2 (middle panel). Yet, the degree of this tendency was considerably affected by whether or not stimulus location was repeated, $F(2,30) = 12.60$, i.e., response repetitions were more likely if stimulus location was repeated rather than neutral or alternated, and more likely if it was neutral than alternated. The RTs very much followed this result pattern, $F(2,30) = 6.37$, although here the difference between the neutral and alternation conditions was not reliable.

Experiment 1C

R1 was initiated as quickly as in the previous experiments (281 ms) but with somewhat less accuracy (8.2% choice errors or anticipations, and 4.6% omissions). A closer look at the data revealed that most errors were associated with conditions requiring a double press (13.6% choice errors), while single-press conditions produced comparatively few errors (2.8%). The most likely reason for this pattern relates to the rather high-temporal demands on double responses. That is, when attempting to perform a double press, participants might sometimes have failed to carry out the second of the two responses in due time, so that an incorrect single press was recognized by the program.
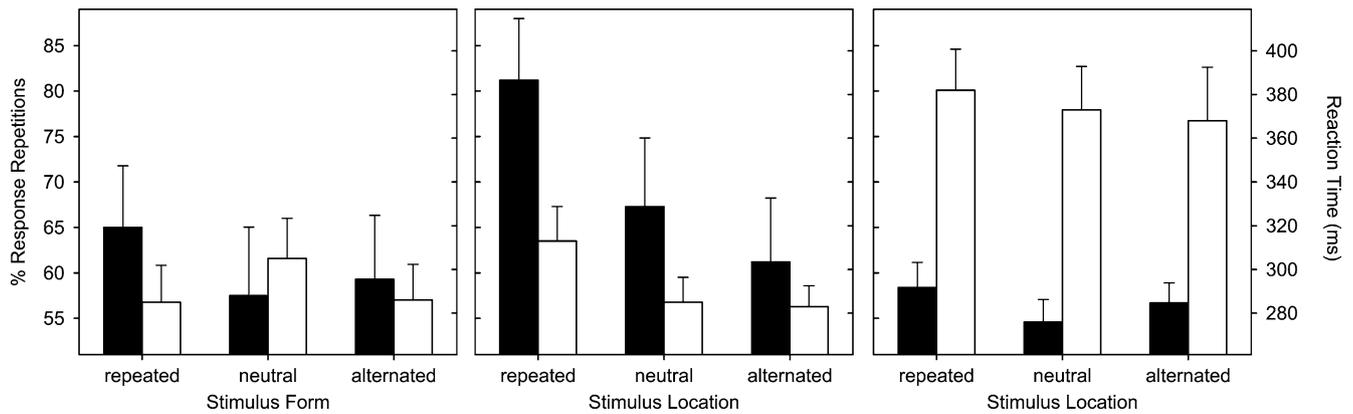
Fig. 2 Experiment 1: percentage of response repetitions (R2 = R1; *black bars*) and reaction times (*white bars*) as a function of stimulus form (S2 same as S1, neutral, or same as alternative S1) in Experiment 1A (*left panel*) and as a function of stimulus location (S2 same as S1, neutral, or same as alternative S1) in Experiments 1B and 1C (*middle* and *right panel*, respectively)

R2 was omitted or incorrectly produced in nogo trials in only 0.3% and performed prematurely in 8.3% of the cases. There was only a very mild, insignificant overall tendency towards response repetition and no indication of a dependency of response-repetition rate on repetition or nonrepetition of stimulus location, $F(2,22) = 1.50$, $p > 0.24$ (see Fig. 2, right panel). To check whether this failure to find an effect might be a mere power problem, two additional analyses were carried out. First, the results from Experiment 1B (a mean difference between stimulus repetition and alternation of 20% with a standard deviation of 20) were used to run a power analysis, which confirmed that ten subjects would have been sufficient to detect an effect of the same size in Experiment 1C (with a power of 0.8, $\alpha = 0.05$, $\beta = 0.2$). Second, a further ANOVA was run on the response choices from Experiments 1B and 1C, with experiment as between-participants factor. Apart from the main effect of stimulus-location repetition, $F(2,52) = 10.26$, the interaction with experiment was significant, $F(2,52) = 6.38$, confirming that stimulus repetition did have a different effect in the two experiments. The RT analysis again followed the pattern observed in the decisions, i.e., the effect of stimulus repetition clearly failed to reach significance, $F(2,22) = 1.01$, $p > 0.37$.

Discussion

The main aim of Experiment 1 was to see whether the interactions between stimulus and response repetition Hommel (1998) observed in the RTs of a forced-choice task can be conceptually replicated in the response-repetition rates of the present, new free-choice design. Indeed, response repetitions were significantly more likely if the form of the stimulus was also repeated. The data pattern suggests that stimulus repetitions were not the only factor that had an impact on response choices. First, there was a (however, unreliable) tendency to

repeat responses, probably a hint to the automatic response facilitation commonly associated with short interresponse intervals (e.g., Soetens et al., 1985). Second, the RTs for R2 were rather short, suggesting that some portion of these responses were selected before S2 came up. However, both of these influences are unlikely to interact with the sought-for stimulus-induced response tendencies so that, if anything, they reduced the variance these latter effects were able to account for. In other words, the observed impact of stimulus repetitions on response choices can be assumed to represent a rather conservative estimate, obtained on top of other, unrelated but nevertheless effective contributions to response selection.

Interestingly, the form-related effect in Experiment 1A could be replicated for location in Experiment 1B. The size of the location-based effect was even larger than the form-based effect, $F(2,60) = 4.96$, $p < 0.01$, suggesting that location codes can be integrated with response codes just as, or even better than form codes can. On first sight, the observation that spatial information is integrated even though of no nominal task relevance might be taken to indicate a crucial, obligatory role of location in stimulus processing. However, note that location did possess a somewhat hidden task relevance even in Experiment 1B. Although the location of the stimulus could safely be ignored the location of the responses could not—after all, responses were defined in terms of their relative location! This type of task relevance of location may have "spread" from response to stimulus processing and, hence, primed stimulus-location codes to a degree that enabled their integration with response codes (Fagioli, Hommel, & Schubotz, 2005; Hommel, 2004; Memelink & Hommel, 2005). Indeed, the tendency to repeat a response was unaffected by whether stimulus location repeated or alternated in Experiment 1C, that is, in the absence of a spatially defined response set. By inference, then, we can assume that the integration indicated by the observations in Experiment 1B was due to the backward-priming of

stimulus-location codes by response-preparation processes.

Even though the repeated and alternated conditions followed a clear-cut pattern, the attempt to establish a neutral condition by presenting stimuli as S2 that could not occur as S1 was less successful—at least in Experiment 1A. With respect to response choices the effect of these stimuli was comparable to stimulus alternations, suggesting that all that counts is whether the stimulus is repeated or not. The same pattern can (in some cases) be observed for responses, that is, people tend to treat the sequence of two different responses and the combination of a nogo- and a go-response equally (Hommel, 1998). Even though Experiment 1B shows that under some conditions neutral stimuli do produce results laying in between stimulus repetitions and alternations, the failure to do so consistently led me to drop this condition in the following experiments.

Experiment 2

So far, the findings from Experiment 1 can be sketched as follows: identity-related stimulus features are integrated with the responses they accompany in a more or less automatic fashion while stimulus location is integrated with the response only if primed by the response set. However, the observations underlying these conclusions come from separate experiments and refer to only one identity-related feature (form). Experiment 2 was designed to bring together all the presumably important factors, so that their relative impact and possible context-dependencies can be assessed. Accordingly, participants carried out the task employed in Experiment 1 except that the repetition and alternation of three stimulus features (form, color, and location) was varied orthogonally, and that a spatial and a nonspatial response set was used.

A particularly interesting implication of this design is that it allows assessing whether what is integrated with the response is stimulus features or the whole stimulus object. In the latter case, responses may be repeated only if the whole stimulus, that is, the exact combination of identity-related features (here: form and color) are repeated—as standard accounts of repetition effects seem to imply. In contrast, if "local bindings" between stimulus features and response features are formed, as claimed by Hommel (1998) and Hommel et al. (2001), one would rather assume that the impact of form repetition on response repetition is independent of the impact of color repetition. A further question of interest is whether stimulus location would also produce local effects, hence, affect response repetition independent of other features, or whether its effects would mediate those of other, nonspatial features. Indeed, Kahneman et al. (1992) suggested that object files (i.e., bindings of stimulus features) might be addressed by spatial codes, so that the access to, and

the impact of, object representations may depend on the repetition of spatial location.

Method

Forty-eight adults (30 female and 18 male, aged 17–38 years) participated. They fulfilled the same criteria as in Experiment 1. A randomly determined half of the participants carried out the task with a spatially defined response set (i.e., left vs. right keypresses) and three white left- or right-pointing arrowheads as R1 cues, just as in Experiment 1A. The other half performed the task with a nonspatial response set (i.e., single vs. double keypresses) and the white digits 1 and 2 as response cues, as in Experiment 1C. All participants faced the same array of three vertically arranged gray frames already used in Experiment 1, with the middle frame being reserved for presentation of the response cues. S1 consisted of the uppercase letter X or O, presented in red or green, in the upper or lower frame. Likewise, S2 was a red or green X or O, appearing in the top or bottom frame (go trials), or it was omitted (nogo trials). A session comprised 10 randomly determined practice trials and 2 blocks of 144 randomly ordered trials each. Of these 144 trials, 16 were catch trials with no S2, each preceded by 1 of the 16 possible combinations of R1 identity and S1 form, color, and location. The remaining trials resulted from the 128 possible combinations of R1 identity and S1 form, color, and location, and of S2 representing a repetition or alternation of S1's form, color, and location. In all other respects, including timing and instructions, the method was as in Experiment 1.

Results

R1 was initiated quickly (297 ms on average) and reasonably accurate (2.4% choice errors or anticipations, and 5.6% omissions). R2 was omitted in go trials or carried out in nogo trials in only 1.0%, and performed prematurely in 0.4% of the trials.

Response choices (% response repetitions) and RTs of the second response were analyzed as a function of response set (spatial vs. nonspatial, as between-participants variable) and repetition/alternation of stimulus form, stimulus color, and stimulus location (all within-participants variables). All three stimulus factors produced significant main effects on response choices: form repetition, $F(1,46) = 9.88$, color repetition, $F(1,46) = 10.18$, and location repetition, $F(1,46) = 34.33$, indicating that the rate of response repetitions increased if any of those stimulus features was repeated. However, in contrast to form and color repetitions, the location-related effect was modified by response set, $F(1,46) = 33.04$. As shown in Fig. 3, the effects of form and color repetition were small but of comparable size under both response sets, whereas location repetition yielded a massive effect

with spatially defined responses but no effect at all with nonspatial responses (as confirmed by separate *t* tests). All other effects failed to reach significance, although the interaction of color repetition and location repetition approached the significance criterion, $F(1,46) = 3.84$, $p < 0.056$—indicating a bigger effect of color repetition if stimulus location was repeated (4.1% more response repetitions with color repetition than alternation) than if it was alternated (1.2%). This interaction was not modified by response set, $p > 0.27$.

RTs produced significant main effects of form repetition, $F(1,46) = 7.61$, and location repetition, $F(1,46) = 25.43$, an interaction of location repetition and response set, $F(1,46) = 5.26$, and a not-quite significant interaction of color and location repetition, $F(1,46) = 3.50$, $p < 0.068$.

Discussion

The results fully replicate those obtained in Experiment 1. In particular, repeating form facilitated response repetitions just like in Experiment 1A and repeating location motivated repeating spatial responses (as in Experiment 1B) but not nonspatial responses (as in Experiment 1C). Moreover, color exerted the same effect as form, and it did so independent of form repetition and the response set. Hence, the processing of color

seems to serve the same purpose as processing form. This supports the interpretation that information about the identity of a stimulus receives more attention than information about its location—at least if location is not of direct or indirect task-relevance. Interestingly, with the exception of an unreliable interaction of color and location (which I shall get back to in the General discussion), there was no hint to any higher-order interaction (see Fig. 4 for a visual demonstration). This is in keeping with the assumption that, first, integration takes place between particular features (Hommel et al., 2001), not between objects and responses, and second, the bindings that emerge are local (Hommel, 1998). Also of interest, there was no indication of any mediating role location might have played, such as increasing the impact of stimulus features if stimulus location was repeated. Apparently, then, nonspatial stimulus codes can be accessed and integrated with other codes in a direct, spatially unmediated fashion (Leslie, Xu, Tremoulet, & Sholl, 1998), at least under stimulus conditions as austere as in the present experiments.

Experiment 3

Up to this point the findings revealed different effects of spatial and nonspatial stimulus features with the former being restricted to tasks with a spatial response set. The

Fig. 3 Experiment 2: percentage of response repetitions (*upper panel*) and reaction times (*lower panel*) as a function of the repetition (*rep*) or alternation (*alt*) of stimulus form, stimulus color, and stimulus location, and the response set (spatial vs. nonspatial)
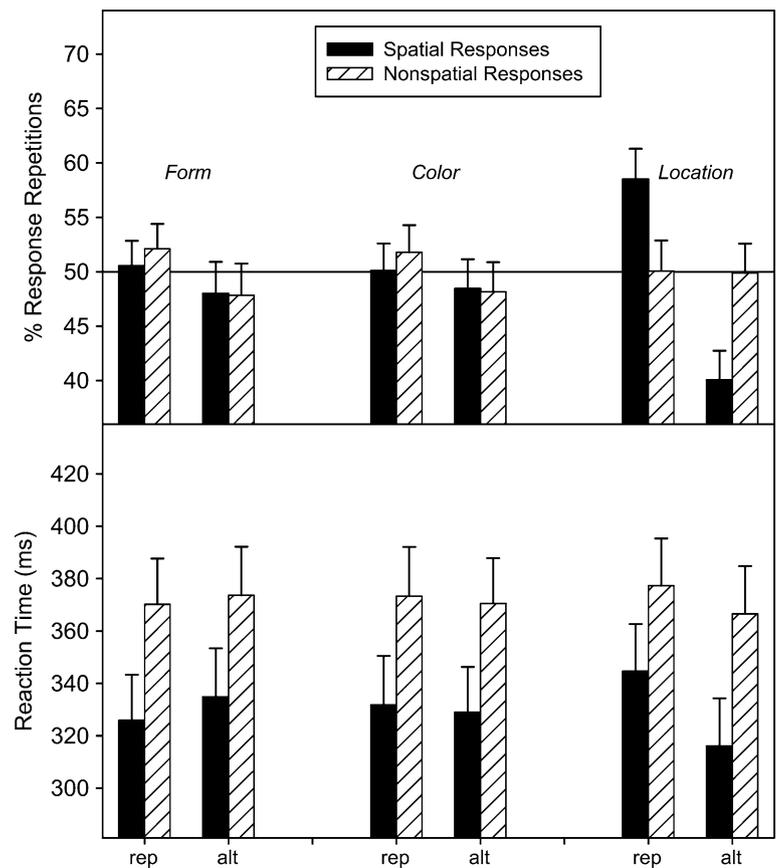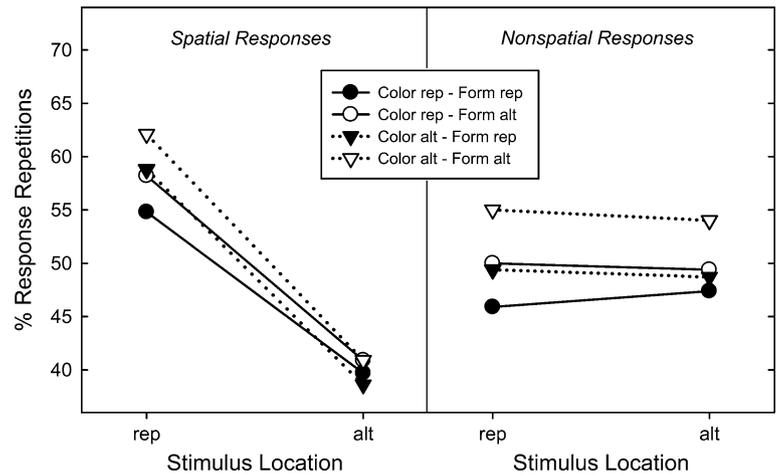
Fig. 4 Experiment 2: percentage of response repetitions as a function of the repetition (rep) or alternation (alt) of stimulus location, stimulus color, and stimulus form, and the response set (spatial vs. nonspatial)

interpretation I suggested assumes a common basis for these two different patterns: stimulus features may be integrated if, and only if, they are somehow task-relevant. In the case of spatial features the "somehow" refers to the dimension that governs response selection and in the case of nonspatial features it relates to the need to discriminate the stimuli (i.e., fixation mark, first and second stimulus) in order to figure out what action they call for. Admittedly, this reasoning is post hoc, at least in the latter case, and other interpretations are possible. For instance, the present tasks are incredibly simple and in no way exhaust the attentional capacities of the participants. As Lavie (1995) has argued, leaving attentional capacity unused may invite the processing of irrelevant information. If so, the observed effects of form and color may merely reflect the fact that the task did not require focusing attention on some particular object or dimension—these features may, in a sense, have picked up free-floating attentional resources. Likewise, it may be that people use form and color features as default dimensions as long as they have no reason to attend other dimensions.

The main problem to rule out such alternative interpretations is that the task does not require attention to focus on a particular dimension, hence, it leaves attention unguided. Therefore, I designed Experiment 3 to control the feature dimensions participants would attend—much along the lines of Hommel (1998). To achieve that, the basic task (with a nonspatial response set) was left intact but participants were asked, after each trial, to indicate the form, color, or location of the last stimulus (S2). In order to avoid any carry-over effects these three dimensions were varied between participants, that is, a given participant would only be asked with regard to one dimension. Although the actual question referred to the second stimulus only, it is likely to make the corresponding feature dimension task-relevant and, hence, affect the processing of S1 as well. Indeed, manipulations of the attentional set regarding S2 have been shown to affect the relative impact of S1 features on performance in the RT version of the present

task (Hommel, 1998). The major question was, of course, whether the introduction of particular attentional sets would modify, or even eliminate, the impact of form, color, or location repetition on the tendency to repeat the response. According to the (hidden-) task-relevance interpretation suggested above, one would expect no such modification in the case of form and color—as participants would make use of these dimensions anyhow—whereas effects of stimulus location should appear in the location-relevant condition only. In contrast, a capacity account along the lines of Lavie (1995) would imply that effects are (mainly) restricted to the task-relevant feature dimension under all three sets.

Method

Eighty-four participants (56 female and 28 male, aged 16–42 years) participated. They fulfilled the same criteria as in Experiment 1, and were randomly and equally assigned to one of the three experimental groups. The method was as in the nonspatial-response group of Experiment 2, except that the basic task was combined with a memory task. That is, at the end of each trial (i.e., 500 ms after R2 was emitted) participants were asked to identify a particular feature of S2 by pressing one of the two marked keys on the numerical keyboard at leisure. In the form-set group participants were always to identify the form, in the color-set group the color, and in the location-set group the location of S2. Trials counted as valid only if the response was correct, otherwise the trial was repeated at a random position in the remainder of the block.

Results

R1 was initiated as quickly as in the previous experiments (290 ms) but somewhat less accurately (4.9% choice errors or anticipations, and 5.1% omissions). R2 was rarely omitted or incorrectly produced in nogo trials

(0.4%) or performed prematurely (0.1%). Memory performance was also very good. The average number of errors in an experimental session was 1.2, 1.4, and 1.8 in the form, color, and location group, respectively. All error trials were excluded from analyses.

Response choices and RTs of the second response were analyzed as a function of attentional set (form, color, and location, as between-participants variable) and repetition/alternation of stimulus form, stimulus color, and stimulus location (all within-participants variables). All three stimulus factors produced significant main effects on decisions: form repetition, $F(1,81) = 25.92$, color repetition, $F(1,81) = 12.69$, and location repetition, $F(1,81) = 6.59$, showing increased response-repetition rates with repeated stimulus features. In contrast to form and color repetitions, the location effect was modified by attentional set, $F(1,46) = 3.75$. Figure 5 shows equally sized effects of form and color repetition under all sets, while the location effect only appears in the location-set group.

Furthermore, there was an interaction of form and location that just missed significance, $p < 0.059$, and a reliable four-way interaction, $F(2,81) = 3.20$. To decompose the latter separate three-way ANOVAs were computed for the three set groups. Both the form and the location group showed some evidence of, however unreliable, three-way interactions, p's < 0.14 and .09,

respectively. Figure 6 shows the underlying data pattern. Further, more detailed analyses traced back the source of these higher-order interactions to a single data point in the location group, the combination of form repetition, color alternation, and location alternation. As can be seen in Fig. 6, most interactions of form and location repetition in the form and the location group followed the same pattern: on top of all main effects response repetitions are more frequent if form repetition goes with location repetition, or form alternation with location alternation, as compared to conditions where one feature is repeated and the other alternates. The only exception is the color-alternated condition in the location group, where the two (hatched) lines are virtually parallel.

The RT analyses did not yield any significant result. The data pattern was uniform, showing only some variation between groups (see Fig. 5).

Discussion

Experiment 3 produced three interesting results. First, the repetition or alternation of nonspatial features affected the tendency to repeat a response in all three groups in comparable ways, hence, independent of which feature dimension was task-relevant. This agrees

Fig. 5 Experiment 3: percentage of response repetitions (*upper panel*) and reaction times (*lower panel*) as a function of the repetition (rep) or alternation (alt) of stimulus form, stimulus color, and stimulus location, and the attentional set
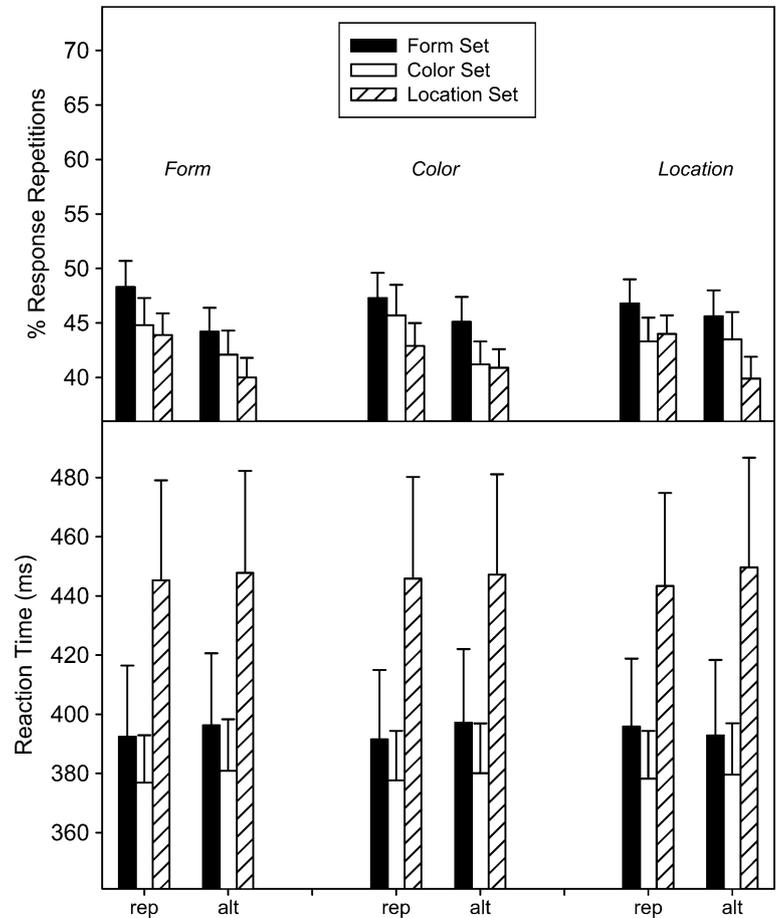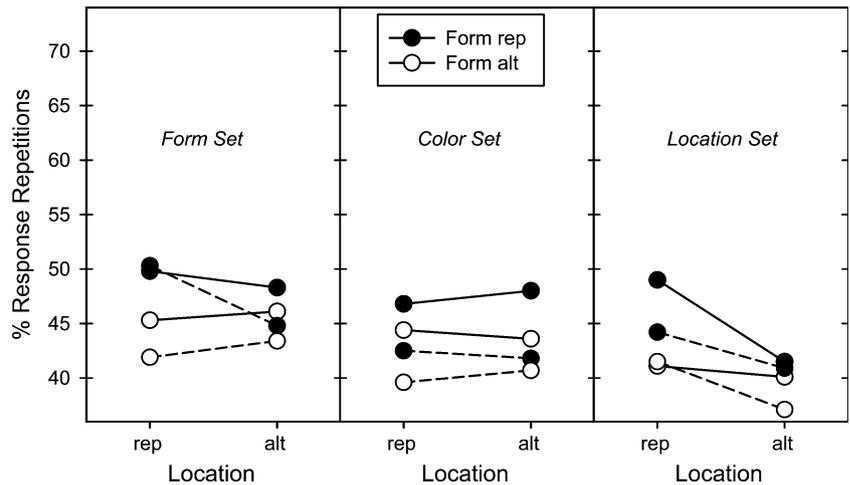
Fig. 6 Experiment 3: percentage of response repetitions as a function of the repetition (rep) or alternation (alt) of stimulus form, stimulus color (*solid* and *broken lines* for color repetition and alternation, respectively), and stimulus location, and the attentional set

with the findings from Experiment 2, where effects of nonspatial features were also independent from the response set, another manipulation of task relevance. Apparently, then, form and color codes are integrated with response codes even if attention is directed to the other nonspatial dimension, and even the degree of integration (as measured by the response-repetition bias) is unaffected by the attentional manipulation.

Second, introducing stimulus location as a relevant feature dimension had the same effect as the response-set manipulation in Experiment 2: repetition and alternation of stimulus location affected response repetitions only if stimulus location was made task-relevant in one or the other way. This supports the interpretation that task-relevance is indeed the crucial factor and not, for instance, processes having to do with manual left versus right responses in particular.

Third, there were some hints to higher-order interactions but these were small, often unreliable, and not overly systematic (and therefore difficult to interpret). As we have seen in Experiment 2, and as we will see in the next two experiments, effects with such characteristics are rather common if more than one stimulus dimension is used (cf., Hommel, 1998). As to be elaborated in the General Discussion, this might suggest that integration of and between feature codes is a matter of degree, that is, not strictly controlled but dependent on the current level of activation the respective feature dimension has.

Experiment 4

The present findings did not reveal strong, reliable indications of higher-order dependencies between repetitions or alternations of stimulus features. Although consistent with earlier observations (Hommel, 1998), this absence of interaction effects has interesting theoretical implications. Authors in the areas of visual attention (e.g., Duncan, 1996; Kahneman et al., 1992) and stimulus–response interactions (e.g., Houghton &

Tipper, 1994; Kornblum & Stevens, 2002) often assume that stimulus information gets access to response representations only after stimulus features have been integrated. In the present context, this would suggest that what is bound are not stimulus features and response features but integrated object representations and action plans. If so, we would expect an increase of response repetitions if a particular object (i.e., combination of stimulus features) is repeated, which amounts to a two-way interaction of stimulus form and stimulus color repetition or, if we consider the spatial-access assumption of Kahneman et al. (1992), a three-way interaction including stimulus location. However, this is not what the results of the present experiments suggest. They suggest that particular features of the stimulus (Experiments 2, 3) are bound with particular features of the response (Experiment 1). Hence, binding seems to be local and feature-based (Hommel, 1998, 2004).

A possible objection against this conclusion might point to the rather Spartan visual conditions the present study creates. Indeed, if we were always facing single stimuli at a time, as our participants did, there would be little need to integrate information into object or event representations, not speaking of attentional selection. That is, wide-spread integration of features may only occur under conditions that make it necessary, hence, if the cognitive system has to keep the representations of different stimuli apart[1]. If so, introducing this necessity should motivate participants to integrate the available information more fully and, thereby, produce the ex-

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[1] The basic idea underlying this (uncommon but not a priori unreasonable) consideration assumes that binding may not be obligatory or necessary for perception or identification to occur. Indeed, if only one event would be represented at a given time there would be no real binding problem: the different features of the event would be coded in different feature maps or systems, but they could still converge on a particular behavior, be that a conscious experience or an overt response, without being "tagged" or "bound". However, binding problems do come into play if more than one event is to be represented at a time, because this raises the question of which features belong to which event. Experiments 4 and 5 aimed at creating such problems.

pected higher-order interactions. Whether this is so was tested in two different ways. In Experiment 5, S1 was accompanied by non-target stimuli, so as to increase the demands on attentional selection. Experiment 4 combined the task employed in the previous experiments with a short-term memory task, which required participants to memorize a letter presented before the actual trial until being probed after the trial. As this memory part of the task can be assumed to require maintaining an integrated object representation while S1 is being presented (Hommel, 2002; Raffone & Wolters, 2001; Stoet & Hommel, 2002), it may be expected to increase the "strength" or "completeness" of S1 integration so as to separate its representation from that of the memorized object. If so, we would expect higher-order interactions between stimulus-feature repetitions to show up more clearly, and more reliably, than in Experiments 2 and 3. For better comparison, I also included a variation of response set along the lines of Experiment 2.

Method

Forty-eight adults (39 female and 9 male, aged 18–43 years) participated. They fulfilled the same criteria as in Experiment 1 and were randomly and equally assigned to the two experimental groups. The groups differed in terms of the responses and response precues used in the main task, analogously to Experiment 2. That is, the spatial-response group pressed a left versus right key, the first precued by left- or right-pointing arrow heads, and the nonspatial-response group pressed a single key once vs. twice, the first response precued by the digit 1 or 2. The remaining method was as in Experiment 3 with the following exceptions. Each trial began with the 3-s presentation of a yellow letter that was randomly drawn from the set of A, B, C, D, E, F, and G. Participants were instructed to hold that letter in mind to reproduce it at the end of the trial. Letter presentation was followed by a blank interval of 1,000 ms and the standard sequence of events involving the R1 precue, S1, and S2. Immediately after R2 was emitted, participants were requested to indicate the memorized letter. This was done by presenting the row of possible letters (A–G) from left to right on the screen. Below each letter, one of the randomly ordered digits 1–7 appeared, and participants were to type in the number below the letter they considered correct. As the order of digits varied unpredictably from trial to trial, this procedure excluded possible motoric or spatial memory strategies, such as touching or holding in mind a particular response key. Trials only counted as valid if the letter was correctly remembered, otherwise the trial was marked and repeated at a random position in the remainder of the block.

Results

R1 was initiated quickly (302 ms) and accurately (2.1% choice errors, no anticipations, and 6.3% omissions). R2

was omitted or incorrectly produced in nogo trials in 0.1% and performed prematurely in 0.6% of the cases. In the memory task, 4.6 and 6.0 errors were made on average in the spatial- and nonspatial-response group, respectively.

Response choices and RTs were analyzed as in Experiment 2. All three stimulus factors produced significant main effects on decisions: form repetition, $F(1,46) = 5.68$, color repetition, $F(1,46) = 6.74$, and location repetition, $F(1,46) = 20.38$, indicating increased response-repetition rates with repeated stimulus features. The only other significant effect was the interaction of response set and location repetition, $F(1,46) = 12.32$, due to that the location effect was entirely restricted to spatial responses (see Fig. 7).

RTs yielded three reliable effects: Spatial responses were initiated more quickly than nonspatial responses (299 vs. 342 ms), $F(1,46) = 5.28$, alternation of stimulus location allowed for faster reactions than repetition (307 vs. 334 ms), $F(1,46) = 55.96$, and this effect was more pronounced with color repetition (303 vs. 338 ms) than color alternation (310 vs. 330 ms), $F(1,46) = 10.56$.

Discussion

The results perfectly replicate those from Experiment 2, and they do so both qualitatively and quantitatively: Form- and color-induced increases of response repetitions that do not depend on response set and a location-induced increase that is restricted to the spatially defined response set. Most importantly, there is again no evidence of any higher-order interaction, even though the addition of the memory task arguably encouraged the integration of S1 features.

Experiment 5

Experiment 4 was an attempt to induce a deeper integration of S1 (and R1) by introducing another stimulus that was to be maintained while S1 was processed. Although previous studies suggest that stimulus and response processing is affected by holding another stimulus in mind (Downing, 2000; Pratt & Hommel, 2003; Stoet & Hommel, 2002), the manipulation did not yield evidence that the binding of stimulus and response features becomes more complex. On the one hand, this may indicate that feature integration across perceptual and action features is local and, thus, does not result in a fully integrated, single whole. On the other hand, the memory task may have been too weak a manipulation to increase the need to integrate S1 sufficiently.

In Experiment 5, S1 no longer appeared alone but was accompanied by a distractor. The distractor appeared some unpredictable time before S1, so that participants could no longer react to the first stimulus onset in the field but were required to identify S1 to a degree that allows successful discrimination from the distrac-

Fig. 7 Experiment 4: percentage of response repetitions (*upper panel*) and reaction times (*lower panel*) as a function of the repetition (rep) or alternation (alt) of stimulus form, stimulus color, and stimulus location, and the response set (spatial vs. nonspatial)
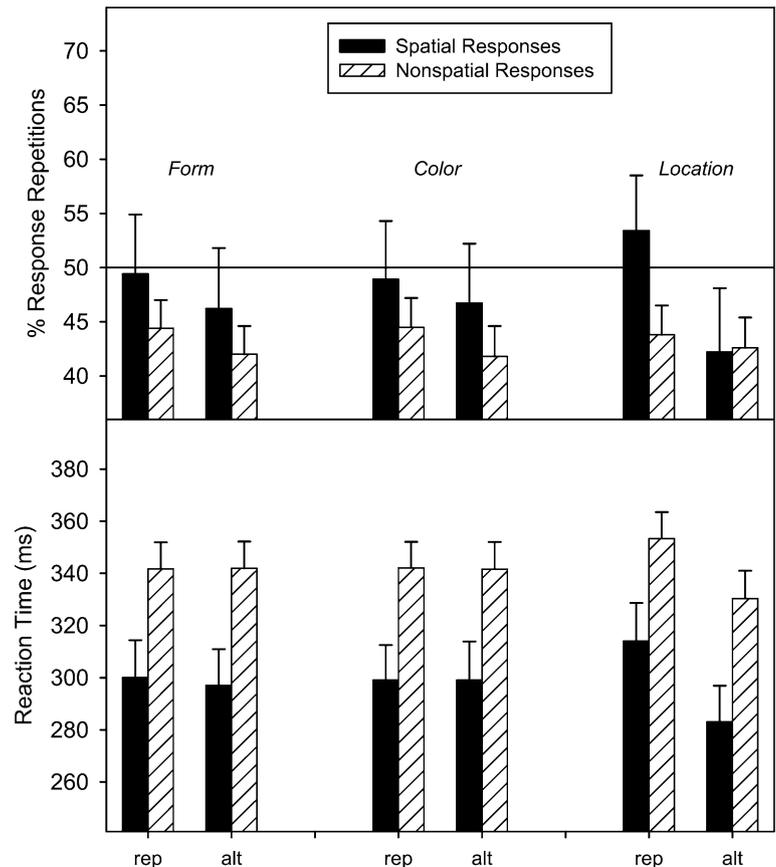
tor—hence, to select S1 against the distractor. This feature of the design required deeper processing of S1 while preserving the theoretically important independence of S1 and R1 (i.e., S1 still served as a response trigger of nominally irrelevant content). If this would affect the integration of stimulus features, and of stimulus and response features, higher-order interactions should emerge.

The distractor was thought to induce deeper processing of S1 by posing a selection problem the solution of which is likely to rely on attentional mechanisms. Attentional selection mechanisms are commonly believed to make use of spatial information, e.g., by providing top-down support for stimuli falling into an established attentional focus (e.g., Posner, 1980; Treisman & Gelade, 1980; Wolfe, 1994). In a sense, then, increasing the selection demands on stimulus intake increases (or even introduces) stimulus location as a task-relevant dimension. In view of the task-relevance effects the present Experiments 2, 3, and 4 revealed for stimulus location, this implies that the design of Experiment 5 might produce effects of stimulus location on response-repetition rates even with a nonspatial response set. That is, the need to select S1 may encourage or require the use of spatial stimulus information, which again will increase the likelihood that stimulus location codes and response codes are integrated.

According to strictly space-based selection models (such as Posner, 1980; Treisman & Gelade, 1980; Wolfe,

1994), this should be true regardless of the particular location of target stimulus and distractor. To test this I employed a task version in which the distractor always appeared in a neutral location (i.e., in the center field of the stimulus frame), that is, in a location where neither S1 nor S2 ever appeared (neutral-distractor condition). However, other models assume that stimulus location does not play a special role but only contributes to target selection if it provides useful, goal-related information (e.g., Bundesen, 1990; Duncan & Humphreys, 1989). From this point of view one may argue that presenting a distractor in a location that is known to be task-irrelevant (apart from hosting the fixation mark) does not suffice to turn stimulus location into a task-relevant dimension. Instead, one would expect stimulus location to become relevant only if distractors appeared in a location that could also be occupied by the target. As it was difficult to predict whether this would affect the results under the present conditions, I also included a task version in which distractors appeared always in task-relevant locations, that is, in the location opposite to the actual target (alternative-distractor condition).

To summarize, Experiment 5 was designed to test two hypotheses. First, the question was whether increasing the demands on stimulus selection would give rise to higher-order interactions indicating true object-action integration. Second, it was assessed whether introducing a distractor stimulus against which S1 was to be selected would make stimulus location (more) task-relevant and,

thereby, foster the integration of stimulus location and (nonspatial) responses.

Method

Sixty-four participants (48 female and 16 male, aged 14–39 years) participated. They fulfilled the same criteria as in Experiment 1 and were randomly and equally assigned to the two experimental groups. The method was as in the nonspatial-response group of Experiment 2 with the following exceptions. The intertrial interval was 1,000 ms, followed by a 1,500-ms presentation of the response cue (digit 1 or 2), and S1, which appeared between 1,000 and 1,200 ms later. The distractor, a white double cross, appeared in between the response cue and S1 but no later than 100 ms before S1; i.e., the interval between response-cue off set and distractor varied randomly between 0 and 1,100 ms, and the interval between distractor onset and S1 onset between 100 and 1,200 ms. Distractor and S1 stayed until the 200-ms presentation time of S1 elapsed. As the distractor made the first part of the task more difficult the maximum RT for R1 was increased to 700 ms. The only difference between the two groups was the location of the double-cross distractor. In the neutral-distractor group it always appeared in the center box while in the alternative-distractor group it appeared in the top or bottom box, opposite to S1.

Results

R1 was initiated quickly (349 ms) and accurately (4.7% choice errors, no anticipations, and 1.9% omissions). R2 was omitted or incorrectly produced in nogo trials in 0.5% and performed prematurely in 0.1% of the cases.

Response-repetition rates and RTs of the second response were analyzed as a function of distractor type (neutral or alternative location, varied between participants) and repetition/alternation of stimulus form, stimulus color, and stimulus location (all within-participants variables). Repetition rates yielded main effects of form repetition, $F(1,62) = 15.00$, color repetition, $F(1,62) = 8.74$, and location repetition, $F(1,62) = 7.49$, all showing more response repetitions with repeated stimulus features. However, in the case of stimulus location this increase in response-repetition rates is only visible with neutral, but not with alternative distractor locations (see Fig. 8). Indeed, although the interaction of location and experiment failed to reach significance, $p > 0.10$, separate analyses revealed a highly significant location effect in the neutral-distractor group, $F(1,31) = 11.46$, $p < 0.005$, but no effect in the alternative-distractor group, $p > 0.48$.

The interaction of form and location repetition was also significant, $F(1,62) = 5.59$, while the interaction of color and location repetition only approached the significance criterion, $p < 0.055$. The patterns underlying

these two effects are shown in Fig. 9. The top panel indicates that response-repetition rates were about the same if form and/or location was repeated, but rates dropped if both features alternated. The bottom panel shows the rather opposite type of interaction involving color and location. Here, response-repetition rates were about the same if form and/or location was alternated, but rates increased if both features were repeated.

The RT analysis revealed two reliable effects. First, an interaction of distractor type and location, $F(1,62) = 12.37$, occurred because repeating stimulus location slowed down responding with distractors in neutral locations (446 vs. 433 ms) but tended to speed up responding with distractors in alternative locations (440 vs. 449 ms). Second, there was a three-way interaction of form, color, and location repetition, $F(1,62) = 5.76$. Separate ANOVAs revealed that form and color interacted if location alternated but not if location was repeated. With location repetition form and color had no effect at all (443, 444, 445, and 442 ms, for repetitions of form and location, location only, form only, and none, respectively). With location alternation, however, RTs were longer if form and color were both repeated or alternated (445 and 444 ms) than if only form or only color was repeated (440 and 434 ms).

Discussion

The first aim of Experiment 5 was to see whether increasing the attentional demands on S1 processing would make the integration of S1 and R1 features more complete, which again should produce higher-order interactions between repetition effects. It is fair to say that the outcome does not suggest a strong increase of feature integration. This is true for the main effects on response repetitions, which were of the same kind and in no way larger than in the previous experiments. And it also applies to the interactions. True, the analyses did reveal one reliable interaction (between form and location) and one not-quite-reliable interaction (between color and location). However, the pattern of the reliable interaction represents the exact opposite of what one would assume from a location-based integration approach along the lines of Kahneman et al. (1992), which suggests effects of nonspatial features to be more pronounced if location is repeated. Worse, both interaction effects do not fit with the corresponding effects obtained in Experiment 3, especially if one uses the location-set group as comparison (considering that location was also relevant in Experiment 5, see below). Finally, the most complex interactions obtained were two-way, suggesting that, if anything, the impact on feature integration was mild and did not lead to a complete integration of a whole stimulus object with the action it accompanied.

With regard to the second aim of the experiment, the most important outcome is that response repetitions were facilitated by repeating stimulus location, even though the effect was reliable only if the target was to be

Fig. 8 Experiment 5: percentage of response repetitions (*upper panel*) and reaction times (*lower panel*) as a function of the repetition (rep) or alternation (alt) of stimulus form, stimulus color, and stimulus location, and distractor location (neutral or opposite to target)
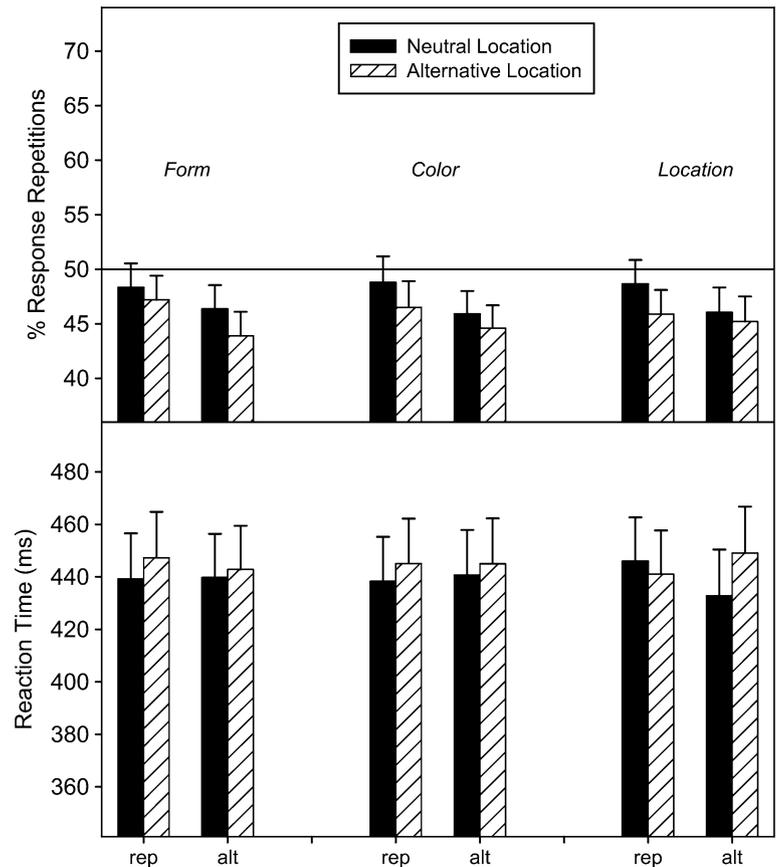
selected against a distractor that appeared in a neutral location. Although the fact that distractor location makes a difference has some theoretical potential, it seems premature to base strong conclusions on it. For instance, given that distractors always preceded the target the location of the distractor was informative in the alternative-distractor condition but not in the neutral-distractor condition. Hence, participants in the alternative-distractor condition may have used the distractor to direct their attention to the opposite location, which may have worked against spatially coding the target (e.g., Stoffer & Yakin, 1994). Whatever the underlying mechanisms, however, what counts for present purposes is the observation that under some conditions increasing the difficulty to select the target stimulus brings into play spatial information (i.e., makes it task-relevant), which again fosters the integration of stimulus location and the accompanying response. Thus, in some sense increasing attentional demands on stimulus processing has effects that are comparable to defining the response set in terms of spatial location.

General discussion

The purpose of this study was to see whether the mere co-occurrence of a stimulus (feature) and a response (feature) would create a spontaneous integration of their codes, an event file in the sense of Hommel (1998). If so,

reactivating the stimulus codes should prime the (currently) associated response code, so that repeating a stimulus should induce a tendency to repeat the response as well. Accordingly, if participants are free to choose one of two responses they should tend to repeat the previous response more if facing a repeated than a non-repeated stimulus. Indeed, all experiments provided evidence that the likelihood of choosing a response repetition increases if features of the stimulus are repeated. Effects of stimulus form and stimulus color were observed in all experiments involving a variation of these features but effects of stimulus location were restricted to particular task contexts. In fact, location effects only occurred if responses were defined in terms of relative location, if participants were asked to attend to stimulus location, or if stimuli were to be selected against distractors appearing in another location. Taken altogether, these findings suggest that stimulus and response features are integrated (become linked) if the dimensions they are defined on are in one way or another relevant to the task at hand.

Strategy and choice

Before jumping to further conclusions we need to consider some objections one might have with respect to the present findings and the method they were obtained with. Given the fact that response choice was free, the
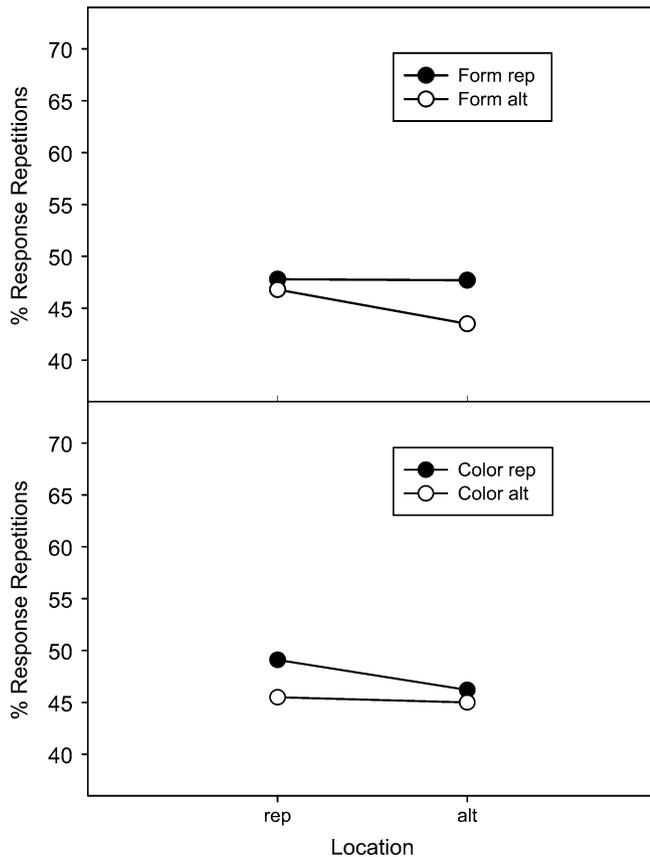
Fig. 9 Experiment 5: percentage of response repetitions as a function of the repetition (rep) or alternation (alt) of stimulus form and stimulus location (*upper panel*), and of stimulus color and stimulus location (*lower panel*)

most obvious factor to consider is choice strategies. Indeed, there can be little doubt that participants applied such strategies, the clearest hint being the overall tendency to repeat responses in Experiment 1. Fortunately, most strategies one can think of can be expected to work against and, if anything, conceal the possible biasing impact of stimulus–response integration. For instance, the general strategy to repeat or alternate responses will motivate choosing responses before S2 even comes up and, thus, reduce the variance S2-induced effects can account for. One might object, though, that participants may have instructed themselves to do what the outcome shows, that is, they may have "intentionally" produced response repetitions in case of stimulus repetitions and response alternations in case of stimulus alternations (a frequent first guess of colleagues I share my findings with).

Although not implausible at first sight, such an objection faces a couple of serious empirical and theoretical problems. First, if participants really instructed themselves like this, one would expect them to produce 100% response repetitions with stimulus repetitions and 0% with stimulus alternations. Although this would nicely satisfy the requirement to perform the two responses about equally often overall, the actually

obtained effects were rather small, and rarely exceeded 10% difference in response repetitions with repeated and alternated stimuli. This raises the question of what purpose a stimulus-related self-instruction would serve. True, making an unguided response decision in each trial arguably costs a lot of "mental" effort, as attested by the observation of longer RTs in free-choice than forced-choice tasks (Berlyne, 1957) and by the considerable difficulties participants are known to experience when trying to generate random response sequences (Baddeley, 1966). Hence, using some kind of rule that governs response choices is not unlikely to reduce the cognitive task load. However, this is only true if the rule would be applied at least most of the time, which the data show did not happen. Also, applying a stimulus–response rule based on the relation between S1 and S2 introduces a substantial memory load (as S1 and R1 codes would need to be maintained), which questions the use of it in terms of cognitive costs, especially in the face of another memory task as in Experiments 3 and 4.

Second, in order to account for rate differences of less than 100% one would need to assume that participants violated their self-instruction in a considerable number of trials. To do so they must have either switched to another self-instruction before selecting the respective response, or have added another element to their selection routine, such as "inverting" a selected response into its opposite. Either way, selecting an alternating response to a repeated stimulus should take more time than selecting a repeated response, that is, produce a kind of rule-violation or task-switching cost. If so, one would expect the combination of response repetitions and stimulus repetitions (i.e., the self-instruction–consistent trials) to be especially dominant in the shorter tail of the RT distribution (i.e., associated with short RTs) and the combination of response alternations and stimulus repetitions (i.e., the self-instruction–inconsistent trials) to be mainly restricted to the longer tail of the distribution (i.e., associated with long RTs). Figure 10 shows the Vincentized distributions obtained in Experiments 1A and 1B, computed for each condition across all participants. Apart from a general tendency of all curves to converge at the end of the distribution (indicating that the very long RTs reflect processing factors unrelated to the stimulus conditions), there is no evidence for either a marked reduction of response repetitions with stimulus repetition (see filled triangles) or a considerable increase of response alternations with stimulus repetitions (see unfilled triangles)—not speaking of any crossing-over of the two curves.

Third, how convincing the self-instruction argument is depends not least on the concrete meaning of the terms "instruction" and "strategy". On the one hand, it is clear from the above reasoning that participants had little reason to, and showed little evidence of, consciously intending to react to stimulus repetitions by performing response repetitions. Hence, if we talk about the personal (i.e., not systems) level of analysis and take the terms literally, following the strategy or instructing

Fig. 10 Number of response repetitions (*black symbols*) and response alternations (*white symbols*) in Experiments 1A and 1B as a function of stimulus repetition (*triangles*) or alternation (*circles*) and the associated reaction-time decile
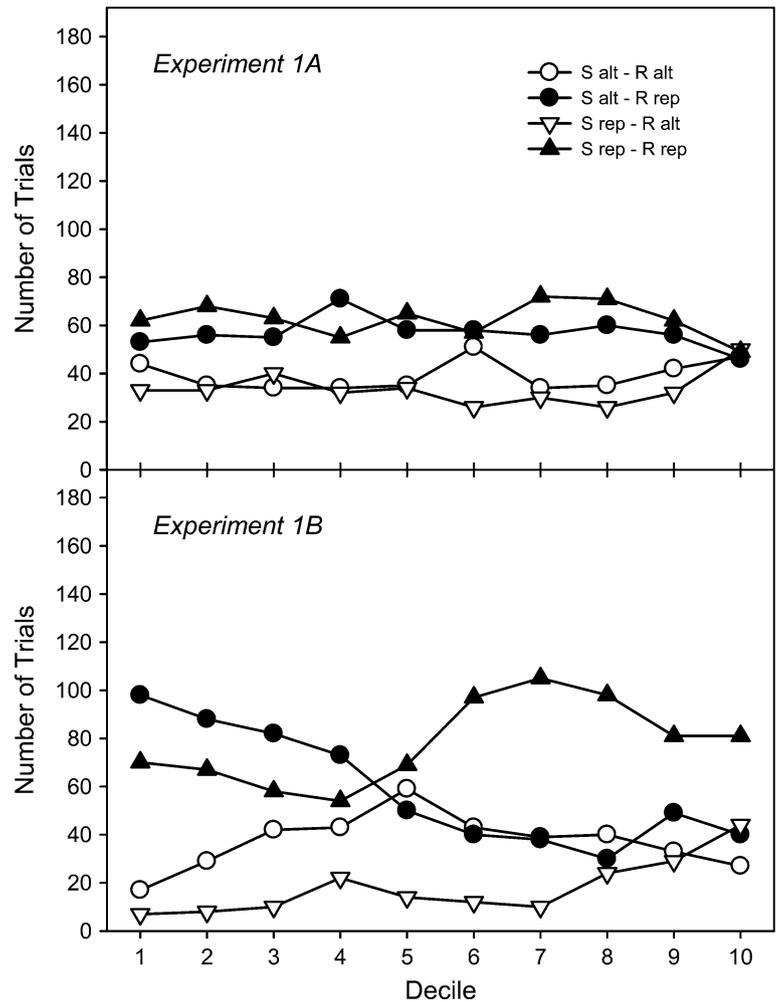
oneself to carry out stimulus-related response repetitions is unlikely to underlie the present findings. On the other hand, though, making "free" response decisions is not a trivial task for a cognitive system and we can expect that it will use any difference in the relative activation of response codes to choose one over the other response. According to the assumption under test one such difference in activation stems from stimulus-response binding, that is, co-occurring stimulus and response features are assumed to be integrated in a way that re-activating the stimulus code will spread activation to the associated response code. Hence, in a sense the proposed integration mechanism, and the consequences it has for the relative activation level of response codes when facing a stimulus repetition, does contribute to solving the problem of response selection. With respect to the system's level of analysis one may call that a strategy, but this use of the term has quite different implications than if applied to the personal level (e.g., participants may not know, and may be unable to tell about their own "strategies"). Most importantly, it does in no way undermine or run counter the interpretation suggested and the conclusions drawn here.

Coding and competition

The major theoretical implications to be drawn from the present findings and those from Hommel (1998) are threefold. First, codes of co-occurring stimulus and response features are (at least temporarily) bound, so that their "behavior" and their impact on performance gets coordinated. Second, the linkages that emerge (event files) are predominantly binary, linking two features each[2]. This may very well depend on the (rather restrained) stimulus conditions used in the available

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[2] In the present study, these binary linkages showed up as main effects of stimulus-feature repetitions on the dependent variable response repetition. These main effects of form, color, and location repetition explained substantial portions of the variance: $\eta^2 = 0.18$–0.43, $\eta^2 = 0.14$–0.24, $\eta^2 = 0.11$–0.31, and $\eta^2 = 0.11$–0.19 in Experiments 2, 3, 4, and 5, respectively. The variance explained by two-way interactions between these three variables (which imply three-way interactions including response repetition) accounted for less variance without exception, $\eta^2 = 0.02$–0.08, $\eta^2 = 0.001$–0.04, $\eta^2 = 0.004$–0.04, and $\eta^2 = 0.001$–0.08, respectively, and the contribution from the three-way interaction (implying a four-way interaction involving all stimulus features and response repetition) was negligible, $\eta^2 < 0.02$ in all cases.

studies and, hence, change into higher-order interactions under situations affording a richer stimulus manifold. Nevertheless, even if such higher-order bindings could be demonstrated under particular circumstances, the outcome of the present and of Hommel's (1998) experiments do suggest that they are not obligatory. Third, the likelihood for a particular stimulus and response feature to be involved in a binding depends on its relevance for the task at hand, although identity-related features (i.e., features individuating a stimulus from others in a given situation) such as form and color in our case may possess a kind of default status (which, however, can also be modified by instruction: Hommel, 1998).

Figure 11 provides a summary of the assumptions and conclusions discussed so far (cf., Hommel, 2004). The basic idea underlying this event-file model is that perceived events (stimuli) and to-be-produced events (planned actions) are cognitively represented in terms of their perceivable features (Hommel, 1997; Hommel et al., 2001), with the latter (and presumably even the former) being associated with particular motor patterns. In Fig. 11, four feature domains are considered: one coding stimulus features that are irrelevant to a task (S_i), two coding stimulus features that are relevant (S_j and S_k), and one response feature that is also relevant (R_x). (Note that relevance is "subjectively" defined here, i.e., the term refers to whatever dimensions a perceiver/actor is *effectively* using to identify stimuli and responses.) Incoming stimulus information is coded in parallel in all the feature maps, as is stimulus-induced or internally generated response activity. Thus, codes representing the respective value of the particular feature (e.g., RED in the COLOR domain) get activated. It is this activation that I assume to produce the automatic facilitation of stimulus and response repetitions at short IRIs (Bertelson, 1961; Hyman, 1953).

Codes can become integrated if they are activated at the same time or, more precisely, if their activations exceed a particular threshold within the same temporal integration window. However, the likelihood of an activated code to become linked to another code is mediated by task relevance. This is implemented by attentional control settings providing top-down support for codes of feature domains that are considered task-relevant (Folk, Remington & Johnson, 1992; Pratt & Hommel, 2003; Wenke, Gaschler, & Nattkemper, 2005). If two given domains are considered relevant, so that their codes receive top-down support, activated codes become linked (as indicated by the striped "event-file" nodes). As pointed out below, perceived relevance can vary (inter- and intra-individually), so that the amount of top-down support and, as a consequence, the likelihood of being linked can vary as well. However, in an experimental task with fast successions of trials it is unlikely that there is only one code active at a time, which calls for two additional, rather uncontroversial assumptions. One is that codes compete for activation within domains, a rather common assumption in network models of attentional selection (e.g., Cohen, Dunbar & McClelland, 1990; Phaf, Van der Heijden & Hudson, 1990). Another is that only the strongest competitor per domain becomes a member of (i.e., is selected for) the emerging binding, hence, codes compete for binding.

This model has some obvious characteristics, which are necessary to account for the present results, and some less obvious characteristics of considerable theoretical interest. As for the more obvious characteristics, the model accounts for the three major findings just summarized. First, it links feature codes in a way that allows for a spreading of activation from one element to the other, this producing co-activation of all members of a binding even under conditions where only one code
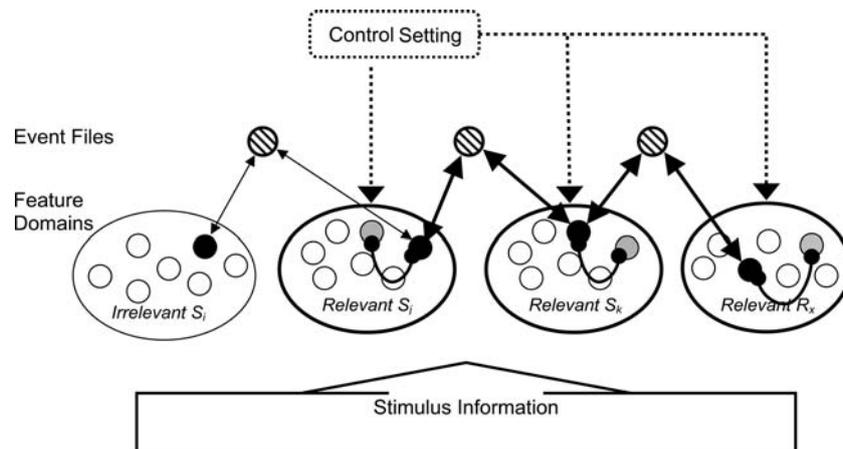

Fig. 11 An event-file model. Registered stimuli and prepared responses are coded through the activation of codes of their features (*black circles*) in the particular feature domains, in which the activated codes compete for selection (i.e., are inhibitorily linked) with other activated features (*gray circles*). Attentional control settings prime task-relevant feature domains, thereby potentiating the upstream contribution of codes selected therein (i.e., winners of the competition). Selected codes form binary conjunctions (event files), represented by striped circles. Members of the same event file prime each other when reactivated. Note that some of the possible event files (e.g., connecting features from S_j to R_x) have been omitted for the sake of clarity

would be needed and activation of the other is counter-productive.

Second, the basic structure of the bindings is binary, just linking two given codes. Given the limited empirical basis at this time the model of course needs to be open to the possibility that the emerging binary linkages engage into higher-order linkages, hence, there may be event-files hierarchies. However, at this point all we need to consider is binary bindings.

And third, the model accounts for the observation that codes are involved in bindings only if their domain is task-relevant in one or another way. Note that the model distinguishes between *feature* domains, not stimulus and response domains (a heritage from Hommel et al., 2001). Accordingly, providing top-down support via attentional control settings for location features impacts any event that is defined in space, be it a stimulus or a response. Hence, attending to response location necessarily involves attending stimulus location, and vice versa—which accounts for the observation that making response location relevant increases the likelihood that stimulus location is integrated.

Importantly, task-relevance need not be defined and represented in a discrete fashion. Thus, it may well be that a particular domain can be more relevant or less relevant, with the top-down support of coding in this domain varying in degree accordingly. The degree of top-down support may even vary within and between people: some may rely more on form, others more on color to identify a stimulus and to discriminate it from other events, and one given person may switch from one criterion to another for reasons of efficiency or boredom. That such variability exists is suggested by the fact that task-irrelevant stimulus features tend to produce effects (i.e., interact with other, relevant features) in a way that is too obvious to ignore and too unreliable and difficult to replicate at the same time, such as in the experiments of Hommel (1998) and some experiments of the present study. Of course, it would be interesting to get a better, more predictable handle on these smaller contributions to feature integration in the future, and this seems to be tenable, e.g., by independently assessing individual or developmentally varying (cf., Odom, 1972) preferences for particular stimulus dimensions.

Let us now turn to some perhaps less obvious characteristics of the model. One, related to the third point just discussed, is that control settings affect stimulus and response domains independently of each other. Thus, it may well be that the top-down support for color, say, is stronger than that for form, so that form codes will be less likely to be integrated with other codes than color codes. Moreover, the thresholds for creating a binding may also vary independently for conjunctions of color and form, color and response location, form and response location, and so forth. Accordingly, bindings may be created between form and color, and between form and response location, but not between color and response location—a pattern that has been observed empirically (Hommel, 1998).

Another important implication of the model is that it allows for what Duncan (1996) called "integrated competition". If two or more given codes are integrated, so Duncan reasons, the fate of one code will have an effect on the fate of the others. Assume, for instance, the red letter X is represented by a linkage of the codes RED and X. Now assume that these codes are competing with the codes of a distractor or a previously presented target, a green O, say. If codes compete for selection in their respective domains we would expect competition between RED and GREEN on the one hand, and between X and O on the other. However, rather than competing independently of each other, the codes will exhibit integrated competition, which means that one code's success or failure in the competition process in its own domain will "spread" to the code it is integrated with in the other domain. In other words, if RED outcompetes GREEN, X will be more likely to win against O—linked codes tend to share a common fate. One implication of this scenario is that repeating a particular feature conjunction should improve performance, a prediction confirmed by numerous studies of repetition phenomena. More unique, however, is the prediction that complete alternations will do better than partial repetitions. For instance, assume the red letter X is following the presentation of a green O, hence, a complete alternation. Determining the correct form of the new stimulus requires the activation of the X code to successfully compete with the remaining trace of O, a process that takes place while in the color domain RED competes with GREEN. Due to integrated competition, the two competition processes are not independent, so that losses of O against X will weaken GREEN in its competition with RED, and vice versa. Accordingly, the fact that O and GREEN are linked will allow X and RED to reach the selection criterion earlier than if O and GREEN were not linked, as in the case of partial repetitions. The same logic can be applied to the integration of stimulus and response codes, which leads to the prediction that repeating or alternating both stimulus and response should yield better performance than repeating the stimulus while alternating the response or vice versa. As outlined in Introduction, this is exactly the pattern observed if stimulus and response repetitions or alternations vary independently (Hommel, 1998).

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