

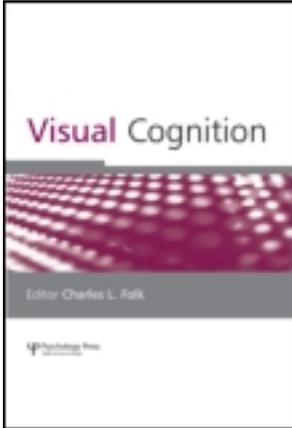
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Working memory updating predicts individual differences in updating stimulus–response episodes

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Evidence suggests that the flexibility of managing (creating and updating) episodic stimulus–response bindings may be related to the updating of working memory (WM). The present study tested whether individual differences in the efficiency of updating stimulus–response episodes are predicted by differences in WM updating (as measured by the N-back task). As expected, individuals who were more accurate in the monitoring and updating of WM were indeed also more efficient in selecting relevant from irrelevant episodic stimulus–response representations. This suggests a crucial role of WM updating in the flexible management of stimulus–response episodes.

Keywords: Binding problem; Dopamine; Event file; N-back.

The primate cortex processes the various features of perceptual events and actions in distinct brain regions (e.g., DeYoe & van Essen, 1988). It has been assumed that the representations of these features are integrated into coherent episodic bindings, such as object files (e.g., Hommel, 2004; Kahneman, Treisman, & Gibbs, 1992). Numerous findings suggest that object files indeed exist (for overviews, see Hommel, 2004; Hommel & Colzato, 2009). For instance, when being presented with multifeatured prime and probe letters, people not only respond faster to letters that they just saw in the prime display

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(a standard priming or repetition effect), but they are particularly fast if the repeated letter also appears in the same location (Kahneman et al., 1992). It seems that registering the prime stimulus is sufficient to bind its feature codes together, so that repeating one or more of its features retrieves the whole binding. If this binding is either entirely unrelated to or fully matches the present feature combination (which is the case with complete repetition), no particular problem arises; but if one or more feature codes mismatch (as in the case of partial repetitions), code conflict is created (Kühn, Keizer, Colzato, Rombouts, & Hommel, 2011), resulting in decision errors (Hommel, 2007), temporal delays (Hommel & Colzato, 2004), or both. Similar observations have been made for auditory features (Mondor, Hurlburt, & Thorne, 2003; Zmigrod & Hommel, 2009), perceptual features from different sensory modalities (Zmigrod, Spapé, & Hommel, 2009), and—of particular importance for the present study—for perceptual and action features (Hommel, 1998). In particular, this last finding suggests that stimulus features and response codes of a given episode are integrated into rather comprehensive “event files”, which are retrieved on the next occasion if at least one element is repeated (Hommel, 2004).

It is important to acknowledge that partial-repetition costs can only be observed if two conditions are met: Feature codes need to be *integrated* in the respective prime trial; and this created binding needs to be *retrieved* in the present (probe) trial. Interestingly, attempts to dissociate these two processes provide evidence that the binding process proper is more or less automatic (Hommel, 2005), whereas the retrieval process is affected by task instructions and individual differences, suggesting at least some degree of control. The automaticity of integration is suggested by observations that it takes place even for stimulus features that the perceiver judges to be unrelated (Zmigrod & Hommel, 2011) and for metacontrast-masked stimuli that the perceiver reports not to have seen (Keizer, Hommel, & Lamme, 2011). The ability to control the retrieval of bindings is suggested by the finding that bindings involving task-relevant, attended features have a stronger impact on behaviour (Hommel, 1998, 2007). Additionally, partial-repetition costs are *more*, rather than less pronounced in individuals with low fluid intelligence (Colzato, van Wouwe, Lavender, & Hommel, 2006), and in young children and elderly participants, as compared to young adults (Hommel, Kray, & Lindenberger, 2011). Given that executive-control functions are related to fluid intelligence (Duncan et al., 2000), not fully developed in young age (Hongwanishkul, Happaney, Lee, & Zelazo, 2005), and impaired in old age (Fisk & Sharp, 2004), these observations suggest that more efficient control functions are reducing the impact of previously created feature bindings, presumably by (better) restricting memory retrieval to the task-relevant information. This is also consistent with recent findings of Keizer, Verment, and Hommel (2010), whose participants received

neurofeedback to increase cortical gamma synchronization. Such training improved memory retrieval in a standard recollection task and reduced partial-repetition costs.

Even though the available evidence suggests that the creation of stimulus–response episodes is relatively automatic whereas the retrieval of such episodes is under top-down control, this conclusion is indirect in resting on plausibility and the exclusion of alternative interpretations. To provide a stronger basis, the present study was thus aiming to provide somewhat more direct evidence for a link between cognitive control and the retrieval and updating of stimulus–response episodes. Our rationale was to assess individual differences in the ability to monitor and update one’s working memory (WM)—an ability that is commonly considered to be an essential component of cognitive control (Miyake et al., 2000)—and to test whether these differences can explain individual differences in the efficiency of controlling the retrieval of stimulus–response episodes. WM updating was assessed by means of the N-back task, which provides a well-established diagnostic measure of WM monitoring and updating (see, Kane, Conway, Miura, & Colflesh, 2007, for a review). In this task, participants are to decide whether each stimulus in a longer stimulus sequence matches the one that appeared n items ago. Whereas the “ $n = 1$ ” version of this task (in which two consecutive stimuli are to be related) serves as a kind of baseline performance, more complex versions ($n = 2$ in the present study) can be assumed to require the online monitoring, updating, and manipulation of remembered information. If WM updating plays a crucial role in the flexible management of stimulus–response episodes, we would expect that individuals who show better performance in the more difficult condition of the N-back show better control of memory retrieval in the event-file task. As in this task memory retrieval is irrelevant and likely to produce cognitive conflict, this would mean that better performance in the N-back task should be associated with smaller partial-repetition costs in the event-file task.

METHODS

Participants

Ninety-two participants (37 male, 55 female), with a mean age of 22.5 years ($SD = 2.3$, range 18–30), served for partial fulfilment of course credit or a financial reward. Written informed consent was obtained from all participants after the nature of the study was explained to them; the protocol was approved by the ethical committee of the department of Psychology at Leiden University.

Procedure

The experiment was controlled by a PC attached to a 17-inch monitor (96 dpi with a refresh rate of 120 Hz). Participants were seated approximately 0.5 m from the screen. All participants were tested individually. Half of the participants began with the N-back task (15-min), the other half began with the event-file task (15-min). Participants were allowed to take a short break (maximal 5 min) between tasks.

Event-file task. The event-file task developed by Hommel (1998) measures binding-related effects by diagnosing *partial-repetition costs* related to (a) combinations of stimulus features (shape and colour in our case) and (b) combinations of stimulus features and the response. One of the perceptual features was task relevant (shape) and the other (colour) was the irrelevant feature for the task. To manipulate the repetition versus alternation of stimulus features and responses, the task comprises of pairs of trials with a prime trial (S1 → R1) followed by a probe trial (S2 → R2) (see Figure 1). The probe trial required a manual binary-choice response (R2) to the shape of the second stimulus S2 (an apple or a banana). The prime trial required a manual response (R1) to the mere onset of the first stimulus (S1). The correct R1 was signalled in advance of S1 (through a left- or right-pointing arrowhead), so that S1 and R1 could be varied independently, which was necessary to create orthogonal repetitions and alternations of stimulus shape and response. As an additional stimulus feature, colour was also varied by presenting the apple or banana in green or yellow (see Colzato, Raffone, & Hommel, 2006). Stimulus colour could repeat or alternate independently of stimulus shape and responses, thus creating a $2 \times 2 \times 2$ factorial design.

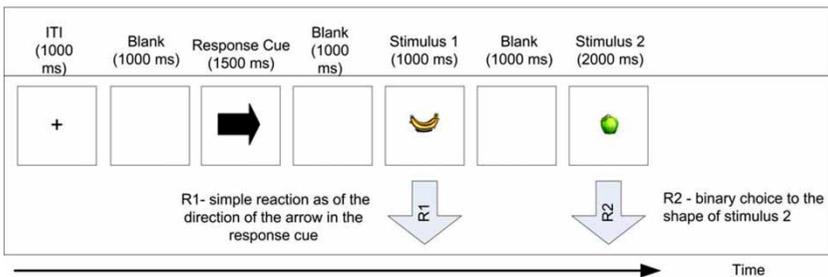


Figure 1. Sequence of events in the event file task. A visual response cue signalled a left or right response (R1) that was to be delayed until presentation of the first stimulus S1 (S1 is used as a detection signal for R1). The second stimulus S2 appeared 1000 ms after S1. S2 signalled R2, a speeded left or right response according to the shape. To view this figure in colour, please see the online issue of the Journal.

The experiment was composed of a practice block with 10 practice trials, which were not further analysed, and an experimental block with 196 experimental trials. The order of the trials was randomized but all eight conditions appeared equally often. Half of the participants responded to the apple and the banana by pressing on the left and right keypress, respectively; the other half received the opposite mapping. The participants were asked to respond as quickly and accurately as possible.

N-back task. The two conditions of the N-back task were adopted from Colzato, Huizinga, and Hommel (2009). A stream of single visual letters (taken from B, C, D, G, P, T, F, N, L) was presented (stimulus–onset asynchrony 2000 ms; duration of presentation 1000 ms). Participants responded to targets (presented in 33% of the trials) and to nontargets. Half of the participants pressed the left shift-key in response to a target and the right shift-key in response to a nontarget; the other half of the participants received the opposite mapping. Target definition differed with respect to the experimental condition. In the 1-back condition, targets were defined as stimuli within the sequence that were identical to the immediately preceding one. In the 2-back condition, participants had to respond if the presented letter matched the one that was presented two trials before. The 1-back, and 2-back tasks differ in their amount of memory load and demands on executive control for the processing of information within working memory. RTs were analysed for correct responses only. Each block consisted of four cycles of the same task; each cycle comprised of 32 stimuli.

Statistical analysis. First, for the event-file task repeated-measures ANOVAs were performed by means of 2 (banana vs. apple) $\times 2$ (yellow vs. green) $\times 2$ (left vs. right response) with the repetition versus alternation of response (R1 \rightarrow R2), stimulus shape and colour (S1 \rightarrow S2) as within-participant factors. Note that statistical interactions between shape and colour repetition are related to bindings of stimulus features, whereas interactions between shape and response repetition and between colour and response repetition reflect stimulus–response binding (Hommel, 1998). Partial-repetition costs were calculated as the difference between the reaction times (RTs) for partial repetitions (Feature X repeated and Feature Y alternated, or vice versa) and the RTs for complete repetitions and “complete” alternations. That is, if Features X and Y repeated and alternated, their binding effect B_{XY} would be calculated as $B_{XY} = (RT_{X/alt, Y/rep} + RT_{X/rep, Y/alt})/2 - (RT_{X/rep, Y/rep} + RT_{X/alt, Y/alt})/2$. Binding effects thus correspond to the two-way interaction term of the respective features (and are thus immune to possible, but theoretically less relevant, main effects of feature repetition); a value close to zero means that the repetition effects of the two given features do not interact; a value greater than zero indicates a “binding-type” interaction.

Second, RT on correct trials as well as accuracy expressed as the percentage of the N-back task were analysed using repeated measures ANOVA with load (1-back vs. 2-back) as a within-subject factor. Third, we ran correlation analyses that looked into the association between binding effects and the performance in WM updating. We adopted a significance level of $p < .05$ for all statistical tests.

RESULTS

Event-file task

After excluding trials with missing (> 1500 ms) or anticipatory responses (< 200 ms), mean reaction times (RTs) and proportions of errors for R2 were analysed.

Replicating earlier findings (Hommel, 1998; Hommel & Colzato, 2004), RTs revealed significant interactions between shape and colour, $F(1, 91) = 14.02$, $p < .001$, between response and shape (see Figure 2), $F(1, 91) = 256.49$, $p < .0001$, and response and colour, $F(1, 91) = 17.29$, $p < .001$ —repeating one but not the other feature slowed down responding.

The error rates followed the same pattern: Response interacted with shape, $F(1, 91) = 125.94$, $p < .0001$, and colour, $F(1, 91) = 87.53$, $p < .001$. Both interactions were due to fewer errors in conditions where both features were repeated or both alternated, as compared to conditions where one feature but not the other was repeated (see Figure 2).

N-back task

ANOVAs for both accuracy, $F(1, 91) = 40.11$, $p < .0001$, and RT, $F(1, 91) = 125.94$, $p < .0001$, showed a main effect of load: People were less accurate (83% vs. 92%) and slower (582 vs. 493) in the 2-back compared to the 1-back condition.

Correlations

Pearson correlation coefficients for associations between the individual scores of accuracy in the 1- and 2-back condition and the three types of binding effects are provided in Table 1, together with the corresponding split-half reliabilities (which were reliable for all measures). As expected, accuracy in the 2-back condition, but not in the 1-back baseline, correlated negatively with the size of the binding effect related to the task-relevant stimulus feature (shape) and the response. Hence, being more accurate in WM monitoring and updating was associated with more efficient control over the retrieval of episodic stimulus–response representations (see Figure 3).

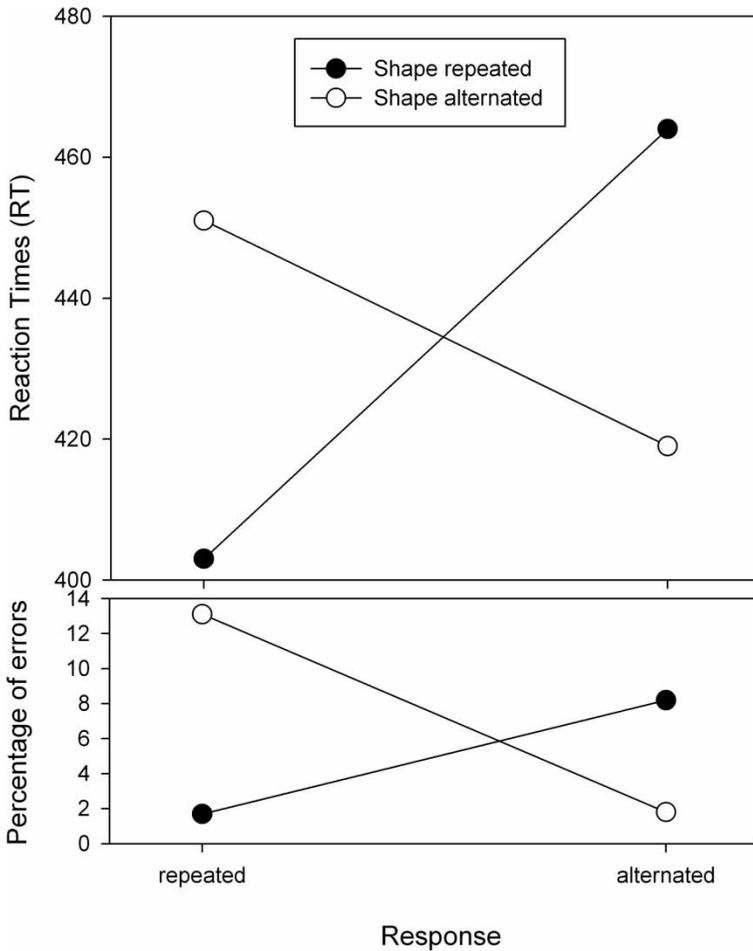


Figure 2. Mean reaction times and error percentages for RT2 as a function of repetition vs. alternation of stimulus task-relevant feature shape and response. Typical binding effects are indicated by patterns showing worse performance for filled circle on the left and unfilled circle on the right (one stimulus feature is repeated while the response alternates, or vice versa).

CONCLUSIONS

Our findings show that individual differences in the efficiency of updating stimulus-response episodes are predicted by differences in WM updating. The results provide rather direct evidence that WM is involved in the handling of stimulus-response episodes. Even though null findings are difficult to interpret, it is interesting to note that WM updating was not related to bindings involving colour, the irrelevant stimulus feature. This suggests

TABLE 1

Correlations among individually computed scores of accuracy in the 1- and 2-back and the shape (task relevant feature)-response, colour-response, and shape and colour binding effects

| | <i>Split-half reliability</i> | <i>Accuracy 1-back</i> | <i>Accuracy 2-back</i> | <i>S-R binding</i> | <i>C-R binding</i> |
|-----------------|-------------------------------|------------------------|------------------------|--------------------|--------------------|
| Accuracy 1-back | .82** | | | | |
| Accuracy 2-back | .74** | .12 | | | |
| S-R binding | .37** | -.13 | -.31** | | |
| C-R binding | .26* | -.14 | -.06 | .12 | |
| S-C binding | .20* | .01 | -.06 | -.15 | -.17 |

** $p < .01$, * $p < .05$. Shape response binding effects : S-R; colour-response binding effects : C-R; shape and colour binding effects : S-C. Split-half reliability estimates (correlations between first and second half of the trials of the respective condition) for the scores are also given.

that WM updating mediates only task-relevant information. Given that both the shape of S2 and R2 were crucial for task performance, participants were likely to keep shape- and response-related information in WM and it may have been this strategic choice that enabled the cognitive control over stimulus-response episodes including these two aspects. In any case, however, the

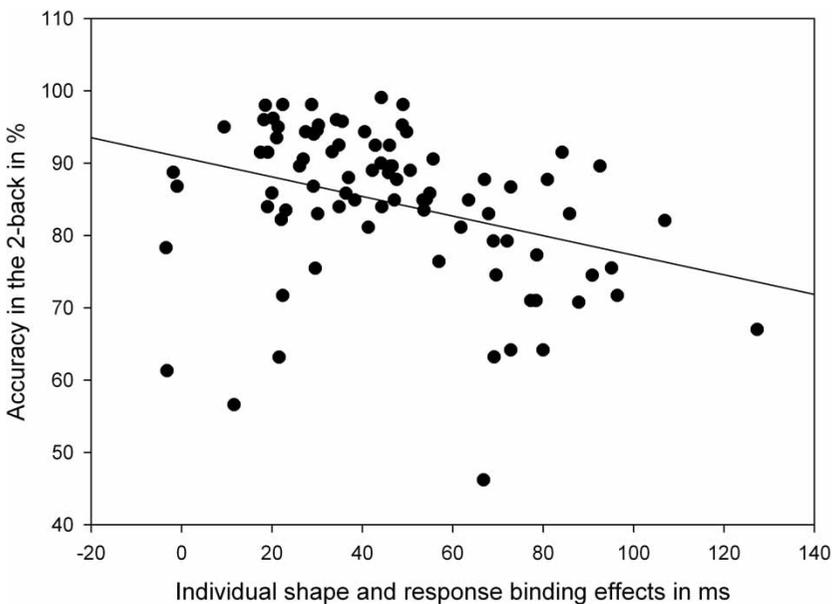


Figure 3. Scatter diagram of individual task-relevant feature shape and response binding effect (in ms) against accuracy in the 2-back (in%).

present observations provide converging evidence that individual differences in the event-file task represent the degree to which people are able to exert control over the episodic retrieval of stimulus–response bindings.

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