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Investing effort during action selection boosts response-response binding and retrieval

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Abstract

Performing two or more responses in close temporal succession leads to short-term bindings between the individual responses that can be retrieved later on. Here we studied the role of cognitive effort for such binding and retrieval. Participants either responded to spatially compatible stimuli (direct mapping condition) or to incompatible stimuli (indirect mapping condition), rendering response selection either easy or difficult. The results of two experiments indicated substantially larger response-response binding and retrieval effects for the indirect mapping condition than for the direct mapping condition. Because bindings between individual responses are thought to be a first elemental step in learning response sequences, the present results indicate that increased effort for individual responses boosts the acquisition of complex sequences.

Imagine a person learning to play an instrument, starting with a simple melody of four notes. If the person is learning to play the piano, it is easy for her to produce the correct tones by pressing the corresponding keys. The only task is to find the correct keys to each written note. Now imagine that this person is learning to play the violin instead. Here it is much more difficult to produce each correct tone. Therefore, the task involves many challenges: finding the correct finger and finger position to each written note, operating the bow, coordinating both hands, etc. It is clear that action control processes differ substantially depending on whether the agent aims to produce easy or difficult individual responses. However, what does such a difference mean for the control of action sequences? At first sight, it is conceivable that the additional effort that is required in case of the violin distracts from learning to play a sequence of tones. Here we show that the opposite is true, however: Increasing effort for individual responses improves rather than impairs the acquisition of response sequences.

Two basic mechanisms that have been discussed to underlie the control of individual responses are binding and retrieval of individual stimulus and response features (Frings et al., 2007; Hommel, 1998; for theoretical approaches, see Frings, Beste, et al., 2024; Frings et al., 2020; Hommel et al., 2001). For instance, responding to a stimulus leads to binding between stimulus- and response features, and repetition of an already bound feature can retrieve the other bound feature(s). Pressing a left key in response to a letter stimulus, for instance, creates a short-term association between features of the stimulus and features of the response; if the letter appears again at a later occasion, retrieving the left response helps if a left response is needed but hinders performance if a different response is required. Crucially, the same binding and retrieval processes affect sequential responses (Moeller & Frings, 2019a, 2019c). For example, executing responses A and B in a row leads to their integration, so that repeating response A, retrieves response B. This retrieval aids performance if response B is needed but can hinder other responses.

Binding and retrieval processes at individual responses and across responses share core characteristics (Moeller & Frings, 2019a, 2019c). Yet, binding effects between responses are generally larger and longer-lasting than most binding effects between stimuli and responses. While stimulus-response binding effects decay within 5 seconds after integration (Hommel & Frings, 2020), response-response binding effects do not show any sign of decay even six seconds after integration (Geissler et al., 2021; Moeller & Frings, 2021).

At first sight, it might seem as if such basic processes like binding and retrieval should operate irrespective of the effort required to execute an action. Rather, effort is known to factor into decisions about which actions or task to execute, leading to a tendency to select the least demanding of two equally rewarding options in both the physical (de Camp, 1920) and cognitive domains (Botvinick & Rosen, 2009; Kool et al., 2010; Neszmélyi & Pfister, 2024). Yet, recent observations for binding and retrieval in individual responses suggest that effort may also be relevant on this level. Schöpper and colleagues (2022) investigated stimulus-response binding effects using a localization task with either direct (i.e., spatially compatible) or indirect (i.e. spatially incompatible) stimulus-response mapping. In the direct mapping condition, participants touched the location of a colored disc at one of four corners on a touchpad. In the indirect mapping condition, they touched the diagonally opposite corner, requiring translation of the stimulus. Binding effects between stimulus color and responses occurred only in the indirect condition, leading the authors to conclude that stimulus- response binding relies on post-selective processing of the stimulus (Schöpper et al., 2022; see also Schöpper et al., 2020). Geissler and colleagues (2024) replicated the behavioral findings and additionally noted that binding effects were linked to task involvement in the dorsolateral prefrontal cortex. As this brain region is tied to executive control (Kim et al., 2012; Owen et al., 2005; Zhang et al., 2017), they suggest that the control needed for stimulus-response translation boosts binding and retrieval.

Together, the studies indicate that an effortful translation from stimulus identity to response increases binding and retrieval effects. For the present purposes we accordingly define effort as increased response-selection or stimulus–response translation demand. Importantly, previous observations analyzing the effect of effort on binding and retrieval effects are restricted to stimulus-response binding, that is, to the representation of an individual response. It is perhaps unsurprising that the effort invested in producing a given response affects the representation of that same response. What remains unknown is whether such effort also affects how this response is represented together with its surrounding actions. The present study addresses this question by testing whether effort invested in an individual response's stimulus-response translation extends beyond that response's own representation to shape its integration into an ongoing action sequence. On the one hand, it is possible that post-selective processing of stimuli in earlier studies very specifically increased attention distributed towards the stimulus-response translation, withdrawing attention from earlier and later actions (Shore et al., 2001). Consequently, one might assume that the magnitude of the effort for making this connection between stimulus and response acted locally, specifically affecting the binding effect between the stimulus and the response. Because bindings can be assumed to be binary (Hommel, 2004; Moeller & Frings, 2019c, 2022), modulations of these processes on the level of individual stimulus-response pairs should not affect binding and retrieval between consecutive responses. In turn, the effort invested in stimulus-response translation would not affect response-response binding effects. Yet, one could also argue that effort invested in each stimulus-response translation should affect bindings between individual responses, as well. Difficult post-selective processing results in a generally more demanding task. This would increase attention and control directed toward task-relevant features in general, resulting in more pronounced processing of both stimuli and responses. Since increased attention (Memelink & Hommel, 2013; Moeller & Frings, 2014) towards responses can be assumed to result in larger response-response binding effects, these effects should be expected to increase

with difficulty of stimulus-response translation. Such a finding would underline that processing differences at the level of individual responses do not act in isolation but are relevant also for action control and representations across multiple actions.

The present study was designed to test the effect of cognitive effort, invested at the level of individual stimulus-response translation on response-response binding effects. We used an adjusted response-response binding paradigm, in which participants executed two prime responses, followed by two probe responses. Here it can be assumed that the two prime responses are integrated, so that repetition of one of these responses as the first probe response starts retrieval of the other prime response, affecting performance in the second probe response. If the retrieved response matches the response required as the second probe response, response execution is facilitated. If the retrieved and required response differ, responding is impaired. Importantly, we manipulated the effort, necessary for stimulus-response translation across different blocks of the experiment. Participants responded to locations on the screen (Experiment 1) or locations on the screen and the numbers 1 through 4 (Experiment 2) either via a direct mapping of stimulus locations or identity to key locations, or via an indirect mapping that required effortful translation of stimulus locations or identities to response locations (see **Figure 1**). If the effort in stimulus-response translation generally increases binding effects, we expected larger response-response binding effects for the high effort condition than for the low effort condition. If differences in stimulus-response binding effects in past studies relied mainly on modulations of stimulus activation, we expected no difference between response-response binding effects for the low effort condition vs. the high effort condition. To anticipate the results, response-response binding effects were indeed larger if stimulus-response translation was difficult than if the translation was easy.

EXPERIMENT 1

Method

Participants. Effect sizes of response-response binding effects in former studies (computed as t/sqrt(n)) were larger than d_z = 0.60 (Moeller & Frings, 2019a: d_z = 0.70 and d_z = 0.80; Moeller & Frings, 2019b: d_z = 0.63 and d_z = 0.84; Moeller & Frings, 2019c: d_z = 0.83). We aimed to find an effect of at least d_z = 0.60 also between the different effort conditions, assuming alpha = .05 and a power of 1-ß = .80. A power analysis with the program G*Power revealed that at least 24 participants were necessary (Faul et al., 2007). Thirty students (29 female) from the University of Trier took part in the experiment. The median age of the sample was 21 years (range 18 to 27). Two additional participants were excluded because they were outliers in prime error rates (more than 30% of all trials included at least one prime error). All participants reported normal or corrected to normal vision and received partial course credit.

Design. The design comprised three within-subjects factors: Response R1 relation (response repetition vs. response change from prime to probe), response R2 relation (response repetition vs. response change from prime to probe), and effort (low vs. high).

Materials. The experiment was programmed using PsychoPy (Peirce et al., 2019; Version v2022.2.2) and run online on Pavlovia (https://pavlovia.org/), with participant recruiting via SONA-Systems. Instructions and fixation marks were shown in white on a grey background, using the native resolution of the participant's monitor. Stimuli were four horizontally aligned white outlines of squares with a side length of 30 pixels that could be filled in red, blue, yellow or green. The distance between squares was 20 pixels. Participants responded with their middle and index fingers by pressing one of four keys on the computer keyboard (D, F, J, and K).

Procedure. Participants were tested online. As a main feature of the task, the screen showed four white outlines of squares that were horizontally arranged around the screen center. On each display, one of the squares turned either red, blue, yellow, or green. The participants' task was to respond to the color change by pressing the corresponding key. Depending on condition, this key either was spatially compatible to the color location (direct mapping) or required a spatial translation (indirect mapping).

Figure 1 (upper part), shows the timeline of an individual trial. Each trial began with the presentation of a fixation cross in the center of the screen that was displayed throughout the trial. After 500 ms a line of four squares appeared 30 pixels above the fixation mark. One of these squares was colored, indicating the location of prime response R1. Note that colors were only used to mark locations while none of the specific colors was associated with any specific response. Upon response execution, the color disappeared and another square was marked by another color, indicating prime R2 location. Upon prime R2 execution the line of squares disappeared for 500ms and was then followed by the first probe display: another line of four squares 30 pixels below the fixation cross. Again, one of the squares was colored (in a color not previously used in this trial) to indicate the location of the first probe response. Upon probe R1 execution, the color disappeared and one of the other squares changed into yet another color, again indicating probe R2 location. This display remained on the screen until probe R2 response. In case of an incorrect response R1 or R2 in prime or probe an error message appeared for 1500ms immediately following the erroneous response, reminding the participant to respond as quickly as possible, but without making errors. The colors red, blue, yellow, and green were used in each trial and were always randomly assigned to prime R1, prime R2, probe R1, and probe R2 displays. That is, a specific color never repeated within the same trial. Every 33 trials participants were allowed to take a short, self-paced break.

The relation of R1 between prime and probe (repetition vs. change) was varied orthogonally to the relation of R2 (repetition vs. change). In R1 repetition trials (R1r), the same

response was required for prime and corresponding probe (R1) display. In R1 change trials (R1c), different responses were required in prime and corresponding probe display. The same was true for R2 repetition trials (R2r) and R2 change trials (R2c). The response required as prime R1 (R2) was never required as probe R2 (R1). These relations resulted in the four conditions R1rR2r, R1rR2c, R1cR2r, and R1cR2c. All four conditions were presented equally often (25% each) in both of two experimental blocks, which resulted in eight conditions. Each block included 128 trials. Crucially, the stimulus-response mapping differed in the two experimental blocks as shown in **Figure 1**. In the direct mapping block, responses were directly mapped to the locations indicated by the squares. That is, if the leftmost square was colored, a response with the left middle finger was required, if the square second from the left was colored, a response with the left index finger was required and so on. In the indirect mapping block, participants were required to translate the stimulus location into a different response location: A colored leftmost square indicated a response with the right index finger, coloring of the square second from the left indicated a response with the right middle finger, the square second from the right indicated a response with the left middle finger, and the rightmost square was mapped to the left index finger (see Kunde, 2001, for a similar response-effect mapping). Before each experimental block, participants practiced the task of the upcoming block for 8 trials (using a random subsample of the experimental trials). Behavioral studies as conducted here are exempt from individual ethical approval at the University of Trier. The experiment was not preregistered. The data and materials for the experiment are available at osf.io/pu8n5.

Results

Our dependent variable of interest was performance in probe R2: If prime R1 and prime R2 were integrated, repeating prime R1 as probe R1 would retrieve the corresponding prime R2, influencing probe R2 performance. For the analysis of response times (RTs), we considered only those trials with correct responses both in prime and probe. The rate of trials with at least

one prime response error was 11.0%. Probe error rates were 4.1% for R1, and 4.5% for R2 (only including trials with correct previous responses). RTs that were more than 1.5 interquartile ranges above the third quartile of the RT distribution of the participant in the respective (low or high effort) condition (Tukey, 1977) and RTs that were shorter than 200ms were excluded from the analysis. Due to these constraints, 17.8% of the trials were excluded from the RT analyses (for per cell trial counts after exclusions, see the **Appendix**). The upper part of **Table 1** shows the resulting mean RTs and error rates across conditions.

We conducted a 2 (R1 relation: repetition vs. change) × 2 (R2 relation: repetition vs. change) × 2 (effort: low vs. high) repeated-measures analysis of variance (ANOVA) on R2 RTs, using the multivariate Pillai's trace as the criterion. The main effects of R1 relation, $F(1,29) = 24.14$, $p < .001$, $\eta_p^2 = .45$, and R2 relation, $F(1,29) = 67.61$, $p < .001$, $\eta_p^2 = .70$, were significant. Participants responded faster if R1 (M = 602ms, SD = 69ms) or R2 (M = 592ms, SD = 63ms) was repeated than if it changed (R1: M = 632ms, SD = 68ms; R2: M = 642ms, SD = 73ms) from prime to probe. The interactions of R1 relation with effort, $F(1,29) = 16.52$, $p < .001$, $\eta_p^2 = .36$, and R2 relation with effort, $F(1,29) = 18.52$, $p < .001$, $\eta_p^2 = .39$, were also significant. The interaction of R1 relation and R2 relation was significant, $F(1,29) = 109.13$, $p < .001$, $\eta_p^2 = .79$, indicating response-response binding. Crucially, this effect was further modulated by effort as indicated by a significant three-way interaction, $F(1,29) = 66.48$, $p < .001$, $\eta_p^2 = .70$. Individual binding effects were calculated as the advantage of probe R1 repetition over probe R1 change in probe R2 repetition trials minus the advantage of probe R1 repetition over probe R1 change in probe R2 change trials: (R1cR2r-R1rR2r)-(R1cR2c-R1rR2c). This effect was larger in the high effort condition (M = 342ms; SD = 191ms, 95% CI [270ms, 413ms]) than in the low effort condition (M = 91ms; SD = 59ms, 95% CI [69ms, 113ms]). However, the main effect of effort was also significant, $F(1,29) = 284.88$, $p < .001$, $\eta_p^2 = .91$. Participants responded much faster in the low effort condition (M = 444ms, SD = 49ms, 95% CI [425ms, 462ms]) than in the high effort condition (M = 790ms, SD = 113ms,

95% CI [748ms, 833ms]). Since generally longer RTs automatically lead to larger numeric differences between conditions as compared to faster RTs as well as retrieval potentially becoming stronger with more time to unfold (e.g., Schöpper & Frings, 2022), we used two different approaches to analyze the response-response binding effect independent of the difference in the mean response time.

First, we calculated cumulative reaction time distributions (Schöpper & Frings, 2022, 2023, 2024; Taylor & Ivanoff, 2005). After applying the cut-off criteria described earlier, we used the 10th, 25th, 50th, 75th, and 90th percentile of probe R2 response times separate for each participant for each condition in each effort block (for the binding effects in the five percentiles as a function of mean RTs see **Figure 2a**). Visual inspection of these binding effects does not suggest that the difference between the effort conditions stems from a general increase of the binding effect with increasing mean RTs. Response times of the two highest percentiles of the low effort condition ($M_{0.75low}$ = 490ms; $SD_{0.75low}$ = 61ms; $M_{0.9low}$ = 552ms; $SD_{0.9low}$ = 76ms) were about as long as response times in the two lowest percentiles of the high effort condition ($M_{0.1high}$ = 495ms; $SD_{0.1high}$ = 53ms; $M_{0.25high}$ = 590ms; $SD_{0.25high}$ = 66ms). We ran our first control analysis on these more comparable percentiles. This analysis was a 2 (R1 relation: repetition vs. change) × 2 (R2 relation: repetition vs. change) × 2 (effort: low vs. high) × 2 (percentile: 0.1/0.75 vs. 0.25/0.9) repeated-measures ANOVA on probe R2 RT percentiles with the multivariate Pillai's trace as the criterion. The main effects of R1 relation, $F(1,29) = 4.51$, $p = .042$, $\eta_p^2 = .14$, R2 relation, $F(1,29) = 63.75$, $p < .001$, $\eta_p^2 = .69$, and percentile, $F(1,29) = 460.41$, $p < .001$, $\eta_p^2 = .94$, were significant, while the main effect of effort was not, $F(1,29) = 3.46$, $p = .073$, $\eta_p^2 = .11$. Importantly, both the interaction of R1 relation and R2 relation, $F(1,29) = 135.46$, $p < .001$, $\eta_p^2 = .82$, (the binding effect) and its modulation by effort, $F(1,29) = 71.60$, $p < .001$, $\eta_p^2 = .71$, were significant, again with a larger binding effect for the high (M = 352ms, SD = 173ms, 95% CI [287ms, 417ms]) than for the low effort condition (M = 103ms, SD = 76ms, 95% CI [74ms, 132ms]). For the sake of completeness, the interactions of effort with R2

relation, $F(1,29) = 10.11$, $p = .003$, $\eta_p^2 = .26$, effort with percentile, $F(1,29) = 23.74$, $p < .001$, $\eta_p^2 = .45$, R1 relation with percentile, $F(1,29) = 7.04$, $p = .013$, $\eta_p^2 = .20$, R1 relation × effort × percentile, $F(1,29) = 7.21$, $p = .012$, $\eta_p^2 = .20$, R2 relation with percentile, $F(1,29) = 4.61$, $p = .040$, $\eta_p^2 = .14$, R2 relation × effort × percentile, $F(1,29) = 5.58$, $p = .025$, $\eta_p^2 = .16$, R1 relation × R2 relation × percentile, $F(1,29) = 5.55$, $p = .025$, $\eta_p^2 = .16$, and R1 relation × R2 relation × effort × percentile, $F(1,29) = 4.99$, $p = .033$, $\eta_p^2 = .15$,were significant, as well, while the interaction of R1 × effort missed significance, $F(1,29) = 1.52$, $p = .227$, $\eta_p^2 = .05$.

Because this first analysis only used a fraction of the data due to little overlap of reaction time distributions, we conducted another control analyses that included the entire range of responses, corrected for the mean response time in each effort condition. For each participant, we divided the mean RTs of all conditions, used to compute the binding effect, by the mean RT in the corresponding effort condition (e.g., mean RT of R1rR2r in the high effort condition divided by mean RT of the high effort condition). The lower part of **Table 1** shows the resulting corrected mean RTs and error rates. We then calculated individual binding effects for the low and high effort condition. **Figure 2b**, shows the corresponding response-response binding effects. A pairwise comparison indicated a significant difference between the effort conditions, $t(29) = 6.19$, $p < .001$, $d = 1.13$, with a larger binding effect in the high ($M = 0.43$, $SD = 0.23$, 95% CI [0.34, 0.51]) than in the low ($M = 0.20$, $SD = 0.12$, 95% CI [0.16, 0.25]) effort condition.

The same analyses were conducted on error rates to exclude alternative explanations in terms of differing speed-accuracy tradeoffs across conditions. Participants made significantly more errors in the high than in the low effort condition, $F(1,29) = 27.01$, $p < .001$ $\eta_p^2 = .48$. The numerical pattern in the analyses of the corrected error rates[1] was similar to the results in the corrected response times. However, the difference between the binding effects in the low ($M =$

[1] Three participants did not commit errors in any of the low effort conditions, leading to a mean error rate of zero. Since this would have meant to divide by zero for the correction of these error rates, resulting in missing data, we set the corrected error rates in these conditions to one.

1.32, *SD* = 2.16, 95% CI [0.52, 2.13]) and high (*M* = 1.76, *SD* = 1.46, 95% CI [1.22, 2.31]) effort condition was not significant, $t(29) = 1.01$, $p = .319$, $d = 0.19$.

Discussion

We investigated response-response binding effects in two conditions that differed in the cognitive effort, necessary for response selection. Significant binding effects occurred in both the low effort condition (direct mapping) and the high effort condition (indirect mapping). Crucially, the binding effect was larger in the high effort condition, suggesting that the effort required for each individual stimulus-response translation affects binding and retrieval between responses.

Since our main interest lay in binding and retrieval processes between responses, it was crucial to avoid retrieval effects caused by stimulus repetition. In Experiment 1, we therefore took great care to prevent location repetitions between prime and probe displays. Horizontally aligned squares were presented above fixation in the prime display and below fixation in the probe display. Additionally, the colors of the marked squares were randomly assigned across the four stimuli (prime S1, prime S2, probe S1, probe S2), reinforcing the impression that no stimulus was repeated within a trial. Nevertheless, one might argue that the prime and probe shared the same horizontal arrangement of squares, differing only in their vertical position on the screen. Consequently, the stimulus feature "position within the horizontal line of squares" varied systematically with the response position. In turn, we cannot exclude the possibility that binding of this feature to the corresponding response could have influenced the results of Experiment 1. To address this concern, we conducted a conceptual replication of Experiment 1 that eliminated the possibility of stimulus feature repetition within a trial.

EXPERIMENT 2

Experiment 2 was a close replication of Experiment 1, with the difference that the type of stimuli always differed between prime and probe displays. To exclude stimulus feature repetition within one trial, participants responded to the position of a colored square as in Experiment 1 during the prime, and to the identity of a number during the probe, or vice versa.

Method

Participants. Power calculations were the same as in Experiment 1. Note that this procedure, including the target effect size of $d_z = 0.60$ is highly conservative because the actual effect size of the impact of effort on response-response binding and retrieval amounted to d_z = 6.19/sqrt(30) = 1.13 in Experiment 1. Thirty students (26 female) from the University of Trier took part in the experiment. The median age of the sample was 25 years (range 18 to 45). One additional participant was excluded because they were an outlier in prime error rates (more than 30% of all trials included at least one prime error). All participants reported normal or corrected to normal vision and received partial course credit or monetary compensation.

Design. The design again comprised three within-subjects factors: Response R1 relation (response repetition vs. response change from prime to probe), response R2 relation (response repetition vs. response change from prime to probe), and effort (low vs. high). In addition, we varied between participants whether prime responses were indicated via numbers and probe responses via marked locations or vice versa.

Materials. The experiment was programmed using PsychoPy (Peirce et al., 2019; Version v2024.1.5). Instructions and fixation marks were shown in white on a grey background. Stimuli were the four digits 1, 2, 3, and 4, and four horizontally aligned white outlines of squares

with a side length of 30 pixels that could be filled with a lime color. The distance between squares was 20 pixels. Participants responded with their middle and index fingers by pressing one of four keys on the computer keyboard (D, F, J, and K).

Procedure. Participants were tested in individual noise-reducing acoustic booths. The procedure was similar to that in Experiment 1 with the following differences. Participants responded to the location of a colored square only in either the prime or the probe, and to individually presented numbers (1, 2, 3, or 4) in the probe or prime, respectively, see **Figure 1** (lower part). In turn, no stimulus feature could repeat from prime to probe displays. Both the horizontally aligned squares and individual numbers were presented in the center of the screen. To indicate each prime (probe) response, one of the squares turned lime green. For half of the participants prime responses were indicated via colored squares and probe responses were indicated via numbers, and for the other half of the participants prime responses were indicated via numbers and probe responses via colored squares. For colored squares the mapping was identical to Experiment 1: either direct or indirect, depending on effort condition. The mapping for the numbers was similar (see **Figure 1**): in the low effort condition, 1 was mapped to the left middle finger, 2 was mapped to the left index finger, 3 to the right index finger, and 4 to the right middle finger. In the high effort condition, 1 was mapped to the right index finger, 2 to the right middle finger, 3 to the left middle finger, and 4 to the left index finger (Dehaene et al., 1993). The experiment was not preregistered. The data and materials are available at osf.io/pu8n5.

Results

Our dependent variable of interest was again performance in probe R2. For the analysis of RTs, we used the same exclusion criteria as in Experiment 1. Due to these constraints, 19.8%

of the trials were excluded from the RT analyses (for per cell trial counts after exclusions, see the **Appendix**). The upper part of **Table 2** shows the resulting mean RTs and error rates across conditions. The rate of trials with at least one prime response error was 9.0%. Probe error rates were 4.2% for R1, and 5.2% for R2 (only including trials with correct previous responses).

In a 2 (probe task: marked location vs. numbers) × 2 (R1 relation: repetition vs. change) × 2 (R2 relation: repetition vs. change) × 2 (effort: low vs. high) repeated-measures ANOVA on R2 RTs, using the multivariate Pillai's trace as the criterion, neither the binding effect, $F(1,28) = 2.11$, $p = .157$, $\eta_p^2 = .07$, nor the modulation of the binding effect by effort, $F(1,28) < 1$, $p = .329$, $\eta_p^2 = .03$ were modulated by the factor probe task. Therefore, we dropped this factor from the analyses and conducted the same 2 (R1 relation) × 2 (R2 relation) × 2 (effort) repeated-measures ANOVA on R2 RTs as in Experiment 1. The main effects of R1 relation, $F(1,29) = 6.24$, $p = .018$, $\eta_p^2 = .18$, and R2 relation, $F(1,29) = 24.77$, $p < .001$, $\eta_p^2 = .46$, were significant. Participants responded faster if R1 (M = 651ms, SD = 92ms) or R2 (M = 641ms, SD = 92ms) was repeated than if it changed (R1: M = 665ms, SD = 91ms; R2: M = 674ms, SD = 91ms) from prime to probe. The interaction of R2 relation with effort, $F(1,29) = 6.81$, $p = .014$, $\eta_p^2 = .19$, was also significant. The interaction of R1 relation and R2 relation was significant, $F(1,29) = 81.80$, $p < .001$, $\eta_p^2 = .74$, indicating response-response binding. This interaction was again further modulated by effort as indicated by a significant three-way interaction, $F(1,29) = 34.14$, $p < .001$, $\eta_p^2 = .54$. The individually calculated binding effect [(R1cR2r-R1rR2r)-(R1cR2c-R1rR2c)] was larger in the high effort condition (M = 208ms; SD = 142ms, 95% CI [155ms, 261ms]) than in the low effort condition (M = 55ms; SD = 51ms, 95% CI [36ms, 74ms]). However, as in Experiment 1, the main effect of effort was also significant, $F(1,29) = 124.30$, $p < .001$, $\eta_p^2 = .81$. Participants responded faster in the low effort condition (M = 520ms, SD = 68ms, 95% CI [494ms, 545ms]) than in the high effort condition (M = 794ms, SD = 144ms, 95% CI [741ms, 848ms]). Therefore, we again additionally analyzed the response-response binding effect independent of the difference in the mean response time.

As in Experiment 1, we calculated cumulative reaction time distributions (Schöpper & Frings, 2022, 2023, 2024; Taylor & Ivanoff, 2005), applied the cut-off criteria described earlier, and used the 10th, 25th, 50th, 75th, and 90th percentile of probe R2 response times separately for each participant for each condition in each effort block (for the binding effects in the five percentiles as a function of mean RTs see **Figure 2c**). Again, visual inspection of these binding effects does not suggest a general increase of the binding effects with increasing mean RTs. For one participant two conditions did not include a sufficient number of observations to calculate five percentiles. This participant was dropped from the following analyses. For the remaining participants, response times of the two highest percentiles of the low effort condition ($M_{0.75low}$ = 576ms; $SD_{0.75low}$ = 80ms; $M_{0.9low}$ = 656ms; $SD_{0.9low}$ = 99ms) were approximately as long as response times in the two lowest percentiles of the high effort condition ($M_{0.1high}$ = 532ms; $SD_{0.1high}$ = 63ms; $M_{0.25high}$ = 634ms; $SD_{0.25high}$ = 91ms). We ran a 2 (R1 relation: repetition vs. change) × 2 (R2 relation: repetition vs. change) × 2 (effort: low vs. high) × 2 (percentile: 0.1/0.75 vs. 0.25/0.9) repeated-measures ANOVA on probe R2 RT percentiles with the multivariate Pillai's trace as the criterion. The main effects of R1 relation, $F(1,28) = 5.19$, $p = .031$, $\eta_p^2 = .16$, R2 relation, $F(1,28) = 33.32$, $p < .001$, $\eta_p^2 = .54$, and percentile, $F(1,28) = 211.84$, $p < .001$, $\eta_p^2 = .88$, were significant, while the main effect of effort did not reach significance, $F(1,28) = 3.31$, $p = .080$, $\eta_p^2 = .11$. Note that RTs were descriptively *longer* in the low effort than in the high effort condition. Importantly, both the interaction of R1 relation and R2 relation, $F(1,28) = 71.89$, $p < .001$, $\eta_p^2 = .72$, (the binding effect) and its modulation by effort, $F(1,28) = 32.49$, $p < .001$, $\eta_p^2 = .54$, were significant, again with a larger binding effect for the high effort condition (M = 219ms, SD = 150ms, 95% CI [162ms, 276ms]) than for the low effort condition (M = 57ms, SD = 67ms, 95% CI [31ms, 82ms]). For the sake of completeness, the interactions of effort with R2 relation, $F(1,28) = 12.34$, $p = .002$, $\eta_p^2 = .31$, effort with percentile, $F(1,28) = 4.88$, $p = .035$, $\eta_p^2 = .15$, R1 relation × effort × percentile, $F(1,28) = 8.97$, $p = .006$, $\eta_p^2 = .24$, and R2 relation × effort × percentile, $F(1,28) = 4.50$, $p =$

.043, $\eta_p^2 = .14$, were significant, as well. The interaction of R1 relation with percentile, $F(1,28) = 3.74$, $p = .063$, $\eta_p^2 = .12$, just missed significance, while all other interactions were not significant, $Fs < 1$, $p > .5$, $\eta_p^2 < .02$.

In the second control analysis, including the whole range of responses, we used the same approach as in Experiment 1 to correct the RTs and error rates in the conditions used to calculate the binding effect, for the mean RT in the respective effort conditions. The lower part of **Table 2** shows the resulting corrected mean RTs and error rates. **Figure 2d** shows the response-response binding effects for RTs. A pairwise comparison indicated a significant difference between the effort conditions, $t(29) = 4.73$, $p < .001$, $d = 0.86$, with a larger binding effect in the high effort condition ($M = 0.26$, $SD = 0.17$, 95% CI [0.20, 0.32]) than in the low effort condition ($M = 0.11$, $SD = 0.10$, 95% CI [0.07, 0.14]).

In the same analyses on error rates, participants made significantly more errors in the high than in the low effort condition, $F(1,29) = 25.26$, $p < .001$ $\eta_p^2 = .47$. The difference between the binding effects of the corrected error rates[2] in the low ($M = 1.06$, $SD = 2.12$, 95% CI [0.27, 1.86]) and high ($M = 1.09$, $SD = 1.81$, 95% CI [0.42, 1.77]) effort condition was not significant, $t(29) = 0.05$, $p = .959$, $d = 0.01$.

Discussion

We replicated the results of Experiment 1 with an improved design. Specifically, we found significant response-response binding effects in a condition with easy as well as in a condition with difficult responding. The binding effect was again significantly larger in the high effort condition as compared to the low effort condition. Notably, this was the case even though stimulus features could never repeat from prime to probe. Therefore, we can conclude that

[2] Error rates in individual conditions in which a participant did not commit any error were again set to one.

binding and retrieval between individual responses is affected by response difficulty directly, independent of stimulus feature repetition.

It should be noted that the Spatial-Numerical Association of Response Codes (SNARC-effect) may have contributed to the general facilitation of responding in the easy mapping condition and impairment in the difficult mapping condition. However, SNARC effects have typically been demonstrated in setups with only two response categories, and we are not aware of any study examining more than two, making it difficult to estimate the effect's influence here. Moreover, idiosyncratic number-space associations appear to coexist with the SNARC effect (Piazza et al., 2006), and implicit mental representations of numbers can vary across individuals (Cohen Kadosh & Henik, 2007; see also Wood et al., 2008). We therefore assume that the spatial representation of the numbers 1 through 4 carried a left-to-right component for most participants, but that this spatial feature was fairly abstract and unlikely to correspond to the actual screen locations of the squares. While we cannot fully rule out a relationship between the numbers' spatial representation and the squares' positions, we maintain that any such relation would be distinct from stimulus repetition.

The effect of effort on the response-response binding effect was numerically smaller in Experiment 2 than in Experiment 1 (Exp.1: η_p^2=.70 vs. Exp.2: η_p^2=.54). If task difficulty alone were driving the magnitude of the binding effects, this would imply that Experiment 2 was substantially easier than Experiment 1. This seems unlikely, however, given that Experiment 2, unlike Experiment 1, required participants to use two mappings in alternation. Instead, switching mappings between integration and retrieval in a binding task has been shown to reduce binding effects, likely due to encoding specificity: retrieval is more successful when more aspects of the original encoding situation are reinstated (e.g., Moeller & Frings, 2019d; Selimi, Frings, Münchau, et al., 2024). It should also be noted that Experiment 1 was conducted online, whereas Experiment 2 was conducted in the lab. Yet, this difference is unlikely to

explain the smaller three-way interaction in Experiment 2, since online data collection typically shows greater variability than lab data, which would predict the opposite pattern (i.e., a larger effect in the lab-based experiment).

General Discussion

In two experiments, we compared response-response binding effects in a low effort condition with those in a high effort condition. While all binding effects were significant, the results of both experiments indicated significantly larger binding effects in high than low effort tasks. Even though response-response binding effects were significant also in the low effort condition, the increased response difficulty in the high effort condition boosted binding and retrieval between responses. Notably, this was the case although differences in effort were due to the difficulty of stimulus-response translation in every single response. That is, the effect of effort invested in an individual response's stimulus-response translation did not remain confined to that response's own representation (see Schöpper et al., 2022), but extended to affect its integration into the ongoing action sequence. Hence, the consequences of effortful response selection are not local to the individual response but propagate to how that response is bound to, and retrieved by, neighboring responses within a sequence. The indirect mapping requires participants to maintain and apply the mapping rule and to selectively process the resulting response code. We propose that this increased task-directed processing raises the probability that consecutive response representations are jointly integrated and/or that a subsequently repeated response feature retrieves the accompanying response representation. In particular, the distribution of attention may have played an important role in this modulation. It has long been known that attention, distributed to a certain feature increases the likelihood of this feature to start a retrieval process (e.g., Memelink & Hommel, 2013; Moeller & Frings, 2014). Increased difficulty of responding via an indirect stimulus-response mapping requires participants to

distribute more attention to each one of their responses. In turn, any bindings that were recently formed (e.g., during a prime) are more likely to be retrieved by the execution of such a closely attended response. Note however that the present behavioral paradigm measures the combined consequences of binding and retrieval and therefore cannot determine whether increased response-selection demand primarily affects integration, retrieval, or both.

Our findings are in line with the observation that increased binding effects in effortful tasks are associated with stronger task involvement of the dorsolateral prefrontal cortex (see Geissler et al., 2024). Such task-involvement might facilitate binding in two ways. On the one hand, this brain region has been shown to be crucial for chunking information (Bor et al., 2004; Bor et al., 2003), which essentially amounts to the binding of multiple features in working memory (Oberauer & Hein, 2012). On the other hand, the dorsolateral prefrontal cortex directly guides action selection (Courtney, 2004; Koechlin & Summerfield, 2007), a process that is essential for the retrieval of the episodic memory traces that reflect binding (Beste et al., 2023; Frings et al., 2020; Hommel, 2009; Wendiggensen et al., 2022).

The effect of effort on response-response binding was particularly large. In similar within-subjects paradigms examining modulations of the response-response binding effect, effect sizes have ranged from $\eta_p^2 = .06$ to $\eta p^2 = .27$. For instance, a switch in effector set between R1 and R2 significantly reduced the binding effect relative to effector set repetitions, $F(1, 17) = 6.37$, $p = .022$, $\eta_p^2 = .27$ (Moeller & Frings, 2019d); the presence of a barrier between responses increased the binding effect, $F(1, 94) = 6.16$, $p = .015$, $\eta_p^2 = .06$ (Selimi, Frings, & Moeller, 2024); and an event boundary between the to-be-integrated responses, $F(1, 38) = 12.93$, $p < .001$, $\eta_p^2 = .25$, as well as a boundary between the retrieving response and the response affected by retrieval, $F(1, 76) = 10.45$, $p = .002$, $\eta_p^2 = .12$, both modulated the response-response binding effect (Moeller et al., 2025). The effects observed in the present study were thus at least twice as large as those previously reported. This suggests that the effort

invested in response selection is particularly relevant for the integration and retrieval of sequential actions.

It is noteworthy that we observed response-response binding effects also in a task without effortful stimulus-response translation. This finding differs from evidence regarding stimulus-response binding effects, which seem to rely on post-selective processing of stimuli and are typically not observed in tasks without sufficiently effortful translation (Geissler et al., 2024; Schöpper et al., 2020; Schöpper et al., 2022). This might be an indication that the minimal stimulus processing, necessary in tasks without stimulus-response translation did play a decisive role in past studies. The same sort of *responses* used in these studies resulted in sufficient activation to be integrated and retrieve each other in the present study. Therefore, it is likely that activation of the stimulus representation in detection tasks or direct response tasks (i.e., localization performance) was simply not sufficient to allow for (stimulus-response) binding or retrieval. Yet, in the current study we analyzed binding only between responses, which can generally be assumed to be activated to a significant degree in order to be executed. This is also in line with the argument that retrieval is possible on a higher level of activation (Schöpper et al., 2024) and the finding that response-response binding effects are generally larger and longer lasting than stimulus-response binding effects (Moeller & Frings, 2021).

The present results bear implications for the intersection between action control and learning. Specifically, it has been shown that high contextual interference during practice produces poorer acquisition performance but superior retention and transfer, whereas low interference (blocked practice) shows the reverse pattern (Magill & Hall, 1990; Shea & Morgan, 1979). This dissociation is generally attributed to increased cognitive effort during high-interference practice, arising either from more distinctive and elaborate encoding of the practiced variations (Shea & Zimny, 1983) or from effortful reconstruction of an action plan forgotten due to interference from intervening trials (Lee & Magill, 1983, 1985). Our results

can be interpreted to extend this account by showing that greater cognitive effort is also associated with stronger binding effects between responses. Note that feature bindings have been interpreted as a first step in a longer learning process leading to long term associations (Frings, Foerster, et al., 2024). Accordingly, enhanced temporary binding and retrieval in effortful tasks may represent an additional mechanism underlying the contextual interference effect.

Effort is also closely linked with learning processes regarding a different dimension. The more we practice a given action, the less effort it requires from us. In turn, if binding or retrieval affect our actions less in tasks that require little effort, we should expect generally smaller binding effects in highly overlearned tasks. Such a decrease in binding effects as a function of (over)learning the responses of a given task has been reported before (Colzato et al., 2006; Fournier et al., 2022). This mechanism is of course also relevant in everyday activities. Remember the violinist novice from the beginning? With practice, the production of each individual sound becomes increasingly easy, as she becomes more proficient (see Ioannucci et al., 2021, for evidence that sequence learning reduces the cognitive costs of sequence execution). Regarding the current results, we have to assume a corresponding change in binding and retrieval effects between these individual actions. Yet, whether this is actually the case and how such changes affect further learning, needs to be investigated in the future.

In conclusion, response-response binding effects were found both for responses that were directly mapped to stimuli so that no stimulus-response translation was necessary and also for more effortful responses with an indirect stimulus-response mapping, requiring such translation. Importantly, response-response binding effects were significantly larger in the difficult as compared to the easy task. That is, binding effects between sequential responses influence our actions more if individual responses are difficult than if they are easy. Ultimately, this could affect learning at different levels of proficiency.

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Table 1. Mean response times (RTs, in ms) and mean error rates (ERs, in percent) and corrected RTs and ERs for probe responses R1 and R2 in Experiment 1, as a function of effort as well as R1 relation and R2 relation between prime and probe.

	Low effort				***High effort***			
	R2 repetition		*R2 change*		*R2 repetition*		*R2 change*	
R2 performance	*RT*	*ER*	*RT*	*ER*	*RT*	*ER*	*RT*	*ER*
R1 change	458	3.1	435	2.7	865	9.0	770	4.8
R1 repetition	407	1.0	475	4.1	640	3.2	886	9.7
Corrected R2 performance								
R1 change	1.03	0.96	0.98	0.88	1.10	1.40	0.98	0.66
R1 repetition	0.92	0.45	1.07	1.71	0.81	0.45	1.12	1.49

Table 2. Mean response times (RTs, in ms) and mean error rates (ERs, in percent) and corrected RTs and ERs for probe responses R1 and R2 in Experiment 2, as a function of effort as well as R1 relation and R2 relation between prime and probe.

	Low effort				***High effort***			
	R2 repetition		*R2 change*		*R2 repetition*		*R2 change*	
R2 performance	*RT*	*ER*	*RT*	*ER*	*RT*	*ER*	*RT*	*ER*
R1 change	528	4.2	519	1.7	834	10.2	777	6.1
R1 repetition	493	2.4	540	4.2	709	5.2	860	9.2
Corrected R2 performance								
R1 change	1.01	1.19	1.00	0.58	1.05	1.38	0.98	0.70
R1 repetition	0.95	0.82	1.03	1.41	0.89	0.74	1.08	1.18

Figure legends

Figure 1. Exemplary sequence of events in one trial in Experiment 1 and both conditions in Experiment 2. Participants performed four responses in each trial: two consecutive responses in each prime and each probe. Responses were indicated by the location of a color patch or by one of the numbers 1, 2, 3, or 4, with different location-response (number-response) mappings in two experimental blocks (low vs. high effort). In Experiment 1, the four colors used to mark locations were randomly assigned to prime R1, prime R2, probe R1, and probe R2 in each trial. In Experiment 2, participants responded to locations in the prime (probe) and numbers in the probe (prime). This is an example of a response R1 repetition and response R2 change trial.

Figure 2. Response-response binding effects in Experiment 1 (a and b) and Experiment 2 (c and d). *(a) and (c):* Mean response-response binding effects in five selected percentiles of the response time distribution (R2 RT) of each participant in the low and high effort condition. The binding effects are calculated as the advantage of probe R1 repetition over probe R1 change in probe R2 repetition trials minus the advantage of probe R1 repetition over probe R1 change in probe R2 change trials: (R1cR2r-R1rR2r)-(R1cR2c-R1rR2c). Error bars depict standard errors of the means. *(b) and (d)*: Response-response binding effects in corrected response times as a function of effort condition: the mean RT (ER) of each condition, necessary to calculate the binding effect, was divided by the mean RT of all responses of the (low or high) effort condition that were included in the analysis (e.g., mean RT of R1rR2r in the high effort condition divided by mean RT of all high effort conditions). The binding effects were calculated as (R1cR2r-R1rR2r)-(R1cR2c-R1rR2c). Error bars depict standard errors of the means.

Figure 1

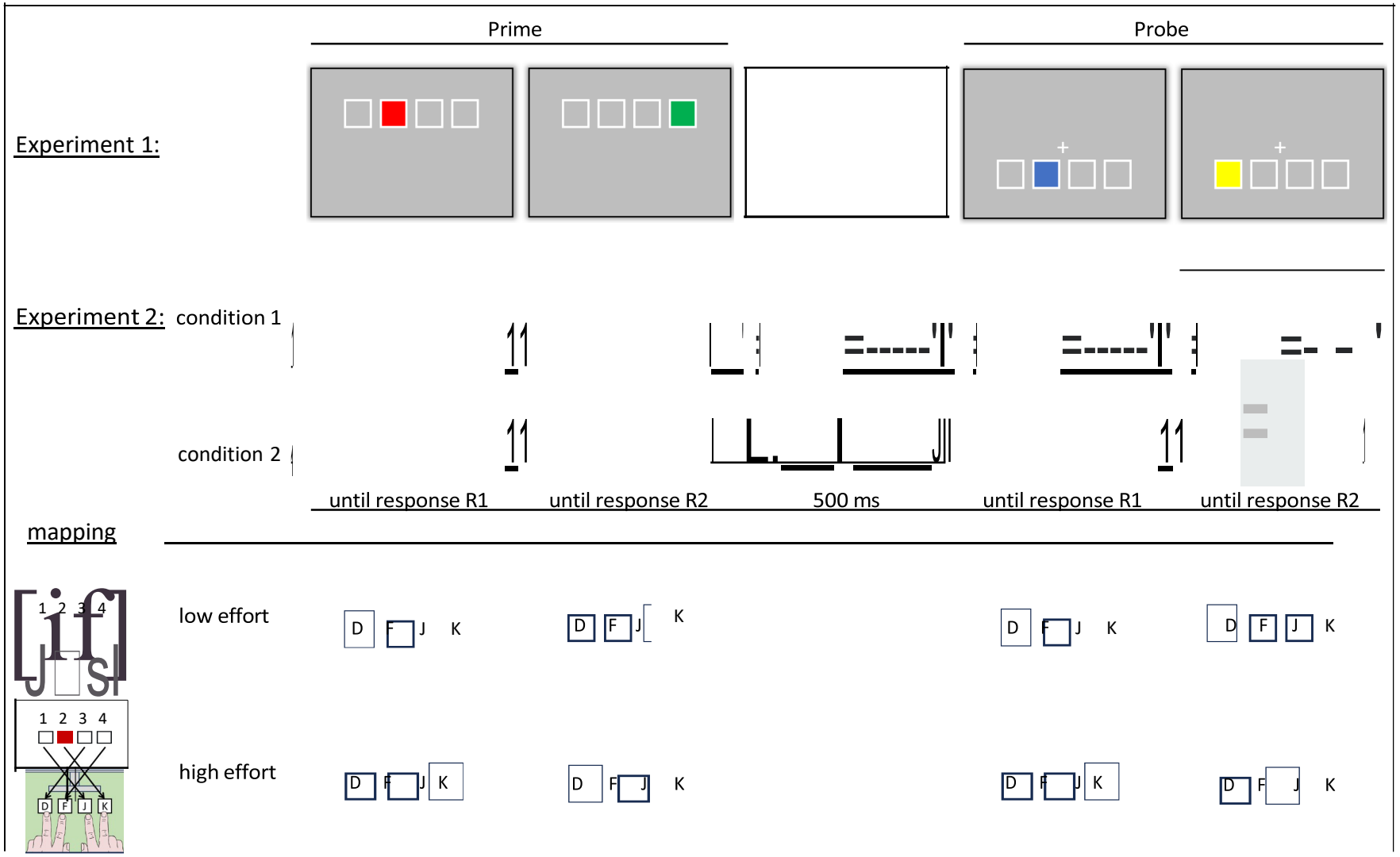
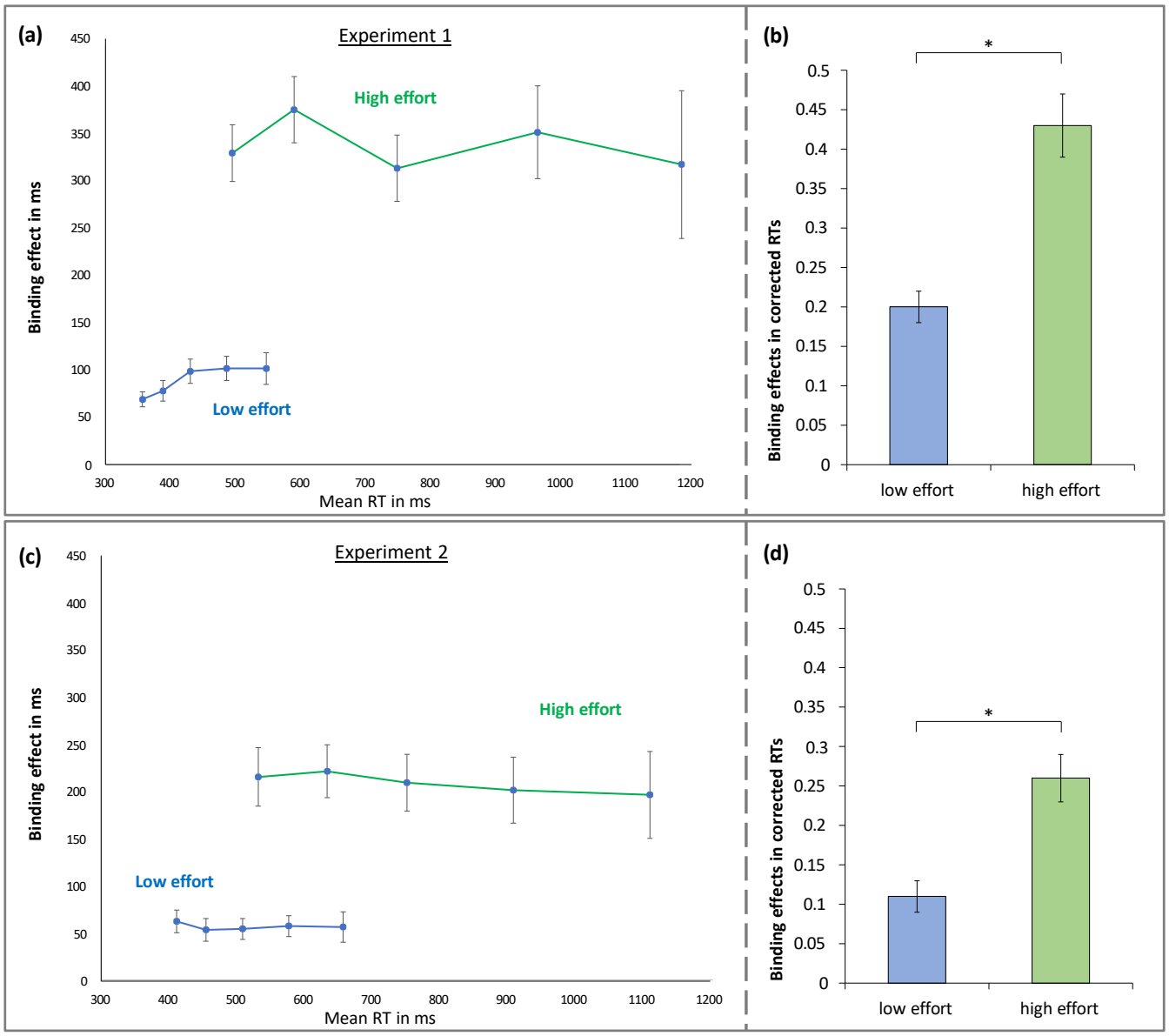

Prime
Probe
Experiment 1:
Experiment 2:
condition 1
condition 2
until response R1
until response R2
500 ms
until response R1
until response R2
mapping
low effort
high effort
1 2 3 4
D F J K

Figure 2


(a)
Experiment 1
High effort
Low effort
Binding effect in ms
Mean RT in ms
(b)
*
Binding effects in corrected RTs
low effort
high effort
(c)
Experiment 2
High effort
Low effort
Binding effect in ms
Mean RT in ms
(d)
*
Binding effects in corrected RTs
low effort
high effort

Appendix.

Per cell trial counts for the response time analyses after exclusions:

Experiment 1		Sum of included trials	Mean sum per participant (SD in parentheses)
Low effort	R1rR2r	876	29 (0.4)
	R1cR2r	819	27 (0.5)
	R1rR2c	818	27 (0.5)
	R1cR2c	839	28 (0.4)
High effort	R1rR2r	728	24 (0.8)
	R1cR2r	672	22 (0.7)
	R1rR2c	675	23 (0.7)
	R1cR2c	690	23 (0.8)

Experiment 2		Sum of included trials	Mean sum per participant (SD in parentheses)
Low effort	R1rR2r	856	29 (0.4)
	R1cR2r	808	27 (0.5)
	R1rR2c	823	27 (0.4)
	R1cR2c	843	28 (0.4)
High effort	R1rR2r	722	24 (0.9)
	R1cR2r	678	23 (0.8)
	R1rR2c	695	23 (0.8)
	R1cR2c	734	24 (0.9)