

Binding and Retrieval of Omitted Responses in Complex Response Sequences

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Abstract

Human action control relies on the close interconnection of action and perception. This is possible through a binding mechanism that integrates distributed features of perceptual and action-related events within sensorimotor representations (event files). Encountering any one of these features later on can retrieve previously integrated features from memory and influence current action. Since actions are represented as their sensory consequences rather than their motor pattern, previous studies suggest that actions can be integrated into and retrieved from event representations even without being executed. However, it is still unclear whether binding and retrieval processes for omitted actions are highly automatic processes or if they can be influenced by higher-order strategies. Here we used sequential tasks to investigate whether binding and retrieval regarding omitted responses is affected by the time to prepare a response, and by the likelihood of response omissions. Results indicate that binding and retrieval are highly adaptive processes that rely on the action planning of responses but operate beyond immediate action contingencies, facilitating efficient action control in future behavior. Data of the experiments are available at OSF (https://osf.io/n79hv/?view_only=4016fea6eb29460f90d9a8fdc842ccba), experiments were not preregistered.

Keywords: ideomotor principle; action planning; actions; binding; retrieval.

Public Significance Statement

Contemporary theories of action control emphasize the remarkable efficiency with which the cognitive system constructs event representations based on anticipatory information alone. Specifically, action planning is thought to suffice for establishing memory traces of upcoming events, which can subsequently be retrieved to guide future behavior in a highly efficient manner. In the present study, we examined the boundary conditions of this automaticity in action control within a continuous stream of action, with a particular focus on situations in which actions are intentionally withheld rather than overtly executed.

Imagine you are making yourself a coffee in the morning. Your machine requires you to press four buttons in a specific sequence to create your favorite brew. But today, in the midst of your routine, you got distracted and forgot to press one of the buttons, the one for extra milk foam. Wouldn't it be remarkable if your coffee machine nevertheless could recognize your intention, despite the omitted action, and still deliver the creamy coffee you wanted? However, while the coffee machine strongly differentiates between actual and imagined input, our cognitive system treats performed and only anticipated actions in strikingly similar ways. That is, both perceived events (perception) as well as movement dependent to-be-generated events (actions) are represented by common perceptual codes.

Actions are the only way humans can influence their environment in goal-directed ways and cognition is assumed to serve this purpose of adaptive action (e.g., Allport, 1987; Herwig, 2015). The underlying cognitive processes of intentional actions were already described in early theoretical approaches such as the *ideomotor principle* (Greenwald, 1970; James, 1890; for a review see Hommel, 2013; Shin et al., 2010), which assumes that actions are selected and initiated by anticipating their sensory consequences (e.g., Kunde, 2001). This requires that both perception and action are represented within shared representations (i.e., the *common code*; Hommel et al., 2001; Prinz, 1997).

Based on the ideomotor principle and earlier binding theories (Hommel et al., 2001; Logan, 1988) the Binding and Retrieval in Action Control framework (BRAC; Beste et al., 2023; Frings et al., 2020) assumes that virtually every human action is shaped by binding and retrieval processes, which integrate features of an action episode and provide adaptive shortcuts for action selection whenever these features are re-encountered. Specifically, the process of binding or integration refers to the automatic process through which temporary associations are formed between two or more feature codes within an action episode, for example between stimulus (e.g., color, shape) and response features (e.g., effector). The outcome of this process

is a common episodic representation of the integrated (sensorimotor) features, referred to as event file (Hommel, 2004b). Following this binding/integration, the process of retrieval refers to a process through which all feature codes stored within an event file are reactivated when one or more event file features reoccur in a subsequent episode (e.g., when a stimulus feature repeats; see Frings et al., 2024, for consensus definitions). Retrieval facilitates the processing of the features and supports the selection of responses consistent with the retrieved information, thereby eliminating the need for computational processes of a currently required response (Henson et al., 2014; Logan, 1988). This means, the retrieval of previously bound features (including the response) can affect current action depending on the match of the retrieved and the currently required response: If the retrieved response matches the currently required response, retrieval facilitates responding and leads to a performance benefit (i.e., lower reaction times or error rates). If a different response is required than the one retrieved, responding is impaired (i.e., increased reaction times or error rates). This pattern of performance costs and benefits due to retrieval is referred to as binding effects.

While stimulus-response bindings are considered central to most simple actions (e.g., Frings et al., 2020; Frings et al., 2007), more recent evidence suggests that bindings also provide a mechanism for linking individual actions into higher-order representations of action sequences. That is, in an ongoing action sequence bindings can be established also between individual responses within an ongoing sequence (Moeller & Frings, 2019a, 2019b). These response-response bindings are commonly studied using sequential paradigms in which dependencies between four consecutive responses are investigated within a prime-probe sequence. In the response-response binding paradigm, participants typically perform a choice reaction time task in which they execute two sequential responses in a prime phase (prime responses R1 and R2) and two sequential responses in a probe phase (probe responses R1 and R2). Crucially, it is assumed that planning and executing the prime responses leads to the

binding of the two respective responses and their integration in an event file. That is, in the prime phase, the process of binding and event file integration is assumed to occur (Frings et al., 2024). Following this binding of individual responses, established response-response bindings can affect subsequent actions in the probe phase via retrieval, depending on the compatibility of the retrieved and currently required responses: If the prime R1 response is repeated as the probe R1 response (R1 response repetition), the retrieval of the associated prime R2 response can facilitate performance when the retrieved response matches the currently required probe R2 response (R2 response repetition), resulting in faster reaction times and lower error rates. Conversely, if only the probe R1 response is repeated (i.e., R1 response repetition) while the probe R2 response differs from the prime R2 response (i.e., R1 response change), retrieval of an incompatible response can impair performance due to a mismatch between the retrieved and required responses¹. Thus, the process of retrieval is assumed to occur in probe where it affects responding (Frings et al., 2024). Accordingly, response-response binding effects are only observed when both the relation of R1 (repetition versus change) and the relation of R2 (repetition versus change) are considered simultaneously, which statistically emerges as an interaction between the factors response R1 relation and response R2 relation. The occurrence of response-response binding effects is interpreted as evidence that prime responses are integrated into an event file and retrieved upon repetition of R1 in probe (Moeller & Frings, 2019b; see also, Frings et al., 2024). In addition to binding effects, the literature has occasionally reported response priming effects, which are typically computed as the performance difference between response repetition and response change trials (e.g., Moeller & Frings, 2019a, 2019b). These priming effects reflect general performance advantages or disadvantages arising from feature-based retrieval processes.

¹ Note that, while response-response bindings have been shown to be independent of the original response order (i.e., the order of prime responses as repeated in the probe; Moeller & Frings, 2019c), the most common implementation of the paradigm restricts repetitions such that responses can only repeat within their respective positions, that is, prime R1 can only repeat as probe R1, and prime R2 can only repeat as probe R2.

Based on the ideomotor principle, it has been assumed that actions are represented as the intended perceptual feedback of a motor pattern (Stoet & Hommel, 1999), it follows that responses in terms of their *action plan* features are integrated into event files (Hommel et al., 2001). Evidence for this assumption comes from studies demonstrating that the mere anticipation of an action (i.e., an already formed action plan that is carried out later on) influences the planning and execution of another action (Stoet & Hommel, 1999). More recently, it was also demonstrated that responses do not need to be executed to retrieve and to be bound to other responses in a response-response binding task, but that merely intending an action – and then omitting its execution – has similar effects on binding and retrieval (Nemeth et al., 2024). Together, these findings highlight that the mere anticipation of a response is sufficient to form feature-based the action plan, so that this response is sufficient to engage binding and retrieval mechanisms, even in the absence of a response being executed.

Importantly, an absence of action is assumed to result either from an *early decision* to omit a response or from the later inhibition of an already initiated action plan (Filevich et al., 2012; for a recent neurophysiological perspective see Ebbesen & Brecht, 2017). Interestingly, some evidence suggests that bindings involving omitted responses occur only when a responding tendency was initially elicited. For instance, in a “planning session”, Stoet and Hommel (1999, Experiment 3) allowed participants ample time to plan an initial response (A_1) before planning and executing a second response (B_1, B_2), following the typical $A_1B_1B_2A_2$ paradigm. In contrast, a “no-planning session” was explicitly designed to discourage advance planning of response A. That is, response planning was experimentally constrained by a very short stimulus-onset asynchrony (100 ms) between the stimuli specifying response A and B, while the stimulus specifying response A remained visible until response B was executed. In addition, participants were explicitly instructed to plan response A only after planning and executing response B. Crucially, the authors observed response-feature overlap costs only in

the planning condition, whereas the opposite pattern emerged in the no-planning condition, leading them to conclude that feature-overlap costs critically depend on intentional action planning (Stoet & Hommel, 1999). In line with this, binding of omitted responses and their contingent effects was only observed when there was an intention, the anticipated action effect, since instructed action omissions did not lead to binding of these responses and their effects (Kühn et al., 2009: Experiment 3).

Importantly for the present studies, earlier studies investigating the influence of planned but not executed actions typically presented omission cues simultaneously with the stimulus associated with the to-be-omitted response or required the eventual execution of the initially planned response at a moment later in time. However, from an ideomotor perspective, a specific prediction emerges when an omission cue *precedes* the presentation of a stimulus associated with the to-be-omitted response. That is, even though the perception or anticipation of action effects can trigger the corresponding motor action, it is reasonable that for adaptive human action control not every instance of perceiving or thinking about action effects inevitably triggers the action. Otherwise, this would result in a constant loop of action effects triggering actions, triggering action effects, and so forth (Konorski, 1967; Moeller & Pfister, 2022; Pezzulo et al., 2007). In fact, early ideomotor approaches emphasize the *desire* to achieve an action goal and thus the sensory effects of an action to be produced (Herbart, 1816, 1825; Laycock, 1860), and, that only those effects that “feel good” are capable of activating a response representation (James, 1890). In addition, when it comes to actions, “the mere presence of another idea will prevent its taking place” (p. 527; James, 1950), which could also be the idea of not to respond to a stimulus. More recent approaches explicitly emphasize the role of motivation in motor response activation. For instance, explicit strategies and expectations that participants adopt throughout an experiment are considered as influencing factors (Watson et al., 2018). The belief that an action will lead to a desired outcome also plays

a crucial role in motor activation, and, importantly, goal-directed actions are assumed to be highly sensitive to affective or motivational value (Eder, 2023; Eder et al., 2015). That is, actions are only executed (and therefore should be cognitively represented) if their perceptual consequences are currently desired, thereby giving them the status of a goal (Wit & Dickinson, 2009; for action initiation that depends on action activation thresholds, see Janczyk & Kunde, 2020; Kunde et al., 2004).

Together, as action planning serves to prepare the cognitive system to produce an *intended* effect, response activation is assumed to be intentional and context-dependent (Elsner & Hommel, 2001; Hommel, 2004a). Thus, the activation of response representations – and consequently, binding effects – for omitted responses should depend on additional intentions, for instance, the timing of the omission cue should influence what is planned. To the best of our knowledge, this emphasis on the context-sensitive and motivation-driven nature of anticipating to-be-expected sensory consequences of planned actions resulting in binding effects has not yet been systematically investigated.

The present study

In the present study, we conducted two experiments to investigate the boundary conditions under which the omission of a response execution may or may not lead to binding and retrieval processes. We focused on whether an omitted response can initiate retrieval of previously bound features. Therefore, we analyzed response-response binding effects as a function of whether a critical response was executed or omitted. Crucially, the two experiments were not designed to be directly compared with each other. Instead, each experiment constitutes a targeted extension of the response-response binding effects for omitted actions reported by Nemeth et al. (2024), implementing one theoretically central modification relative to that prior work.

In both experiments, the probe R1 response served as the critical response whose execution versus omission was manipulated. The logic of the task was that the probe R1 response constitutes the event that can initiate retrieval of the previously bound response. Accordingly, if probe R1 was omitted but response-response binding effects nevertheless emerged, this would indicate that the response was planned thereby able to trigger retrieval of bound features. Conversely, if omitting probe R1 eliminated response-response binding effects, this would indicate that the omitted response did not trigger retrieval, implying that this response was not intentionally planned.

Across both experiments, we used a modified response-response binding task in which participants responded to the identity of individually presented letters and digits. Each trial consisted of a sequence of four responses, within which the execution versus omission of the probe R1 response was manipulated. Salient color cues instructed participants whether to execute or withhold the response, allowing us to dissociate response planning from response execution and to test their respective roles in initiating retrieval.

Experiment 1 examined whether response-response binding effects for omitted actions, as reported by Nemeth et al. (2024), persist when the temporal relationship between stimulus and omission cue is altered. Specifically, whereas Nemeth et al. (2024) presented the omission cue simultaneously with the stimulus, in Experiment 1 the omission cue was presented prior to the stimulus associated with the to-be-omitted response. This manipulation was theoretically motivated by ideomotor approaches emphasizing that intentional action planning depends on the anticipation of sensory consequences. Presenting the omission cue in advance was assumed to prevent intentional response planning, thereby rendering the response incapable of triggering retrieval. Relative to Nemeth et al. (2024), we therefore expected that response-response binding effects would be absent when the retrieving probe response R1 was omitted, while trials in which probe R1 was executed were expected to yield reliable binding effects.

Experiment 2 constituted a second, independent extension of Nemeth et al. (2024) and focused exclusively on the role of omission probability. While Nemeth et al. (2024) employed a 75% execution and 25% omission rate for the critical probe response, Experiment 2 reversed this proportion, using a 25% execution and 75% omission rate. All other aspects of the task, including the temporal relationship between omission cue and stimulus and the general structure of the task, were held constant relative to Nemeth et al. (2024). Our theoretical expectation was that under such conditions of frequent omission, responses could be less likely to be intentionally planned and, consequently, less likely to be bound and retrieved. This would be due to the strategic decision to avoid the planning of probe response R1, as its omission is more likely than its execution. However, if action planning is a conditionally automatic process that can be influenced by current action-related goals but not by higher-order strategies, binding effects for omitted responses should be observed even if the retrieving response R1 is more frequently omitted than executed.

To foreshadow the results, relative to the binding effects reported by Nemeth et al. (2024), we found no significant response-response binding effect when the omission cue was presented prior to the stimulus that was associated with the to-be-omitted response (Experiment 1). In contrast, we found a significant response-response binding effect even when the retrieving response was omitted in 75% of all trials, making its omission the more frequent event compared to its response execution (Experiment 2).

Experiment 1

In Experiment 1, we investigated whether presenting an omission cue before the stimulus that is associated with the to-be-omitted probe response R1 is sufficient to trigger retrieval of the bound response.

Method

Participants

The sample size was calculated according to a previous study that investigated the modulation of omitting the execution of the retrieving probe response R1 on response-response binding effects, which led to a medium-sized effect $d = 0.47$ (Nemeth et al., 2024). Therefore, we planned to recruit at least $N = 61$ participants, resulting in a power of $1 - \beta = .95$ (assuming $\alpha = .05$, two-tailed; using the program G*Power 3.1.9.7; Faul et al., 2007), to obtain a significant medium-sized ($d = 0.47$) modulation of response-response binding effects. 61 participants of Trier University (44 female, 17 male, 58 right-handers) with a median age of 22 years (range: 18–39 years) participated in the experiment. Participants were recruited via Trier University's participant platform (Sona Systems; sona-systems.com) and performed the experiment online on the experimental platform Pavlovia (Peirce & MacAskill, 2018). All participants consented via online form before participating and received course credit as compensation. This study was done in accordance with the ethics guidelines declared by the ethics committee of Trier University. The ethics committee of Trier University declared all simple behavioral studies in accordance with their guidelines exempt from any further examinations by the committee.

Design

The design comprised three within-subjects factors, namely response R1 relation from prime to probe (response repetition vs. response change), response R2 relation from prime to probe (response repetition vs. response change), and omission (no omission vs. probe R1 omission).

Apparatus and stimuli

The experiment was programmed in PsychoPy (Peirce et al., 2019 ;Version 2023.2.3) and ran online via Pavlovia (Peirce & MacAskill, 2018). Instructions and stimuli were shown

in white (Font: Arial; Font size 35 pixels) on a grey background (RGB₂₅₅: 128, 128, 128). Stimuli were the digits 1, 2, 3, and 4 and the letters A, B, C, and D. The outlines of different colored squares (width: 40 pixels, height: 40 pixels) were displayed in black (RGB₂₅₅: 0, 0, 0), yellow (RGB₂₅₅: 255, 255, 0), green (RGB₂₅₅: 0, 128, 0), blue (RGB₂₅₅: 0, 0, 255) or purple (RGB₂₅₅: 128, 0, 128) around the stimuli. These squares served as cues, indicating whether participants should execute a response or refrain from doing so. Participants responded by pressing one of four keys (D, F, J or K) on the computer keyboard.

Procedure

Participants were tested online and were presented with instructions of the experimental procedure on the screen. Participants were instructed to position their middle and index fingers of both hands on the keys D, F, J, and K. Their task was always to press the key corresponding to each individually presented letter or number: using their left middle finger for the letter A and the number 1, their left index finger for B and 2, their right index finger for C and 3, and their left middle finger for D and 4. Participants were encouraged to respond as quickly as possible while also ensuring a high level of accuracy.

All stimuli were presented at the center of the screen. Each trial started with the presentation of an asterisk (*) at the center, signaling participants to initiate the trial by pressing the space bar, followed by a 500 ms blank space (see **Figure 1A**). Then a black square was presented for 250 ms. This was followed by the first prime digit or letter, surrounded by a black square and indicating prime response R1, until the participant pressed one of the four response keys. Again, a black square was presented for 250 ms, followed by the second prime stimulus surrounded by a black square indicating prime response R2 until a response was detected. This was followed by a 500 ms blank space (response-stimulus interval; RSI). Then a colored square appeared for 250 ms: In 75% of all trials (omission condition: *no omission*) a blue, green, or purple square appeared (each 25% of the no omission trials). These cued the participants that

they would have to execute the following probe response R1. In the next display, the same-colored square that was presented one display earlier surrounded the probe R1 stimulus. In 25% of the trials (omission condition: *probe R1 omission*), first a yellow square was presented for 250 ms, after that the probe R1 stimulus appeared, again surrounded by a yellow square, which cued the participants to not execute their probe response R1. In no omission trials, the presentation of the probe R1 stimulus ended upon response detection, that is, when the participant's response was registered by the keyboard. In omission trials, the probe R1 display duration was determined individually based on the participant's average reaction time in probe R1 no-omission trials, continuously updated across the experiment. Finally, another black square was presented for 250 ms, which was followed by the second probe stimulus always surrounded by a black square, indicating probe response R2, which remained on screen until response detection. Between the trials, a blank screen appeared for 500 ms (inter-trial interval; ITI), before the asterisk indicated that the next trial could be started.

In 50% of the *omission* trials, participants were asked at the end of the trial to indicate which stimulus was shown in the yellow square by pressing the key on the keyboard corresponding to the identity of the stimulus (i.e., if the stimulus was A, they had to press the A on the keyboard; if the stimulus was 1, they had to press the 1 key on the keyboard). After a response was detected, the trial proceeded with the instruction to place the fingers back on the four response keys (D, F, J, K) and the trial ended by pressing the space bar. Every 48 trials, participants were prompted to take a short break.

All factors were varied orthogonally and trialwise. In R1 repetition trials (R1r), the same response required as prime response R1 was also required as probe response R1. In R1 change trials (R1c), a different response was required as prime response R1 and probe response R1. In R2 repetition trials (R2r), the identical response required as prime response R2 was also required as probe response R2. In R2 change trials (R2c), a different response was required as

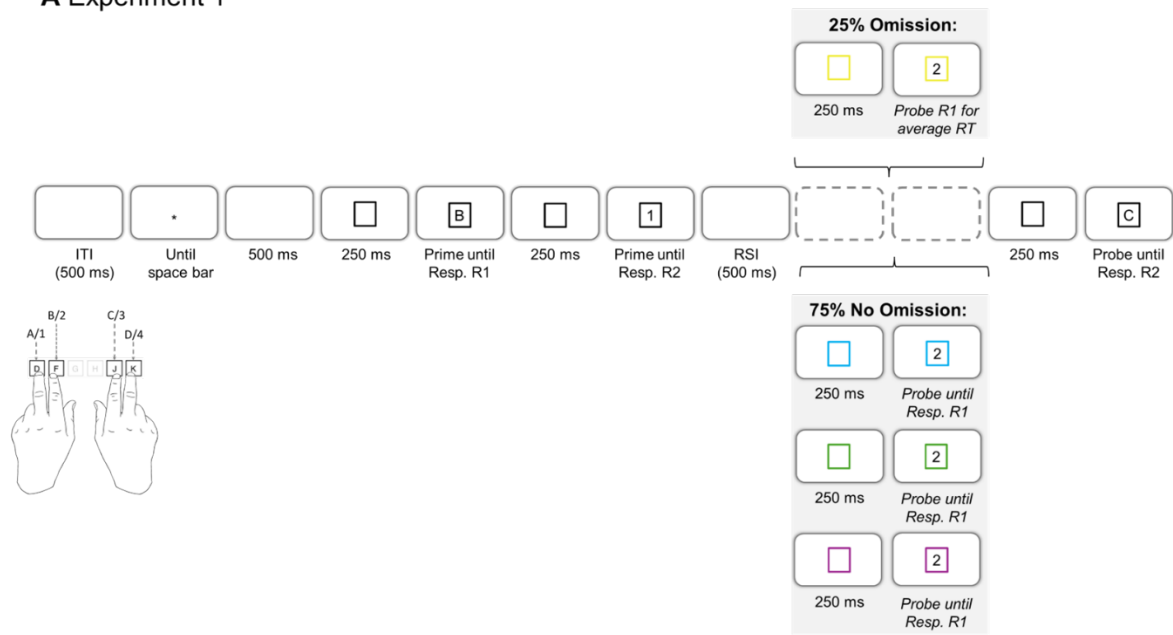
prime response R2 and probe response R2. Response repetitions were always restricted to their respective positions: R1 responses could only repeat as R1, and R2 responses only as R2. Sequence of trials was randomized for each participant. For all trials, stimuli did not repeat from prime to probe. The identity of stimuli (letter vs. number) was determined randomly by the experimental program and was constrained by the response-response binding logic: For each trial, the program randomly selected a stimulus for the first prime response (R1). In response-repetition trials, the probe stimulus corresponded to the alternative stimulus mapped to the same response (e.g., “1” followed by “A”), whereas in response-change trials, the probe stimulus was randomly selected from the set of stimuli mapped to a different response, irrespective of stimulus category (letter or number). The experiment block included 480 trials (120 of each of the four conditions R1rR2r, R1rR2c, R1cR2r, R1cR2c).

Before the experimental block, participants completed a practice phase consisting of 16 trials. Participants who made more than 15% errors repeated the practice block. The practice trials were identical to the experimental trials, with the sole exception of feedback. During practice, participants received performance-contingent feedback after both prime and both probe practice displays as well as after the stimulus assessment (for a correct response: ‘correct’; for a wrong response: ‘WRONG!’; Translated from German, “richtig” and “FALSCH!”). In contrast, during the main experiment, feedback was only provided immediately following erroneous responses. Apart from this difference in feedback, the practice phase did not differ from the experimental block.

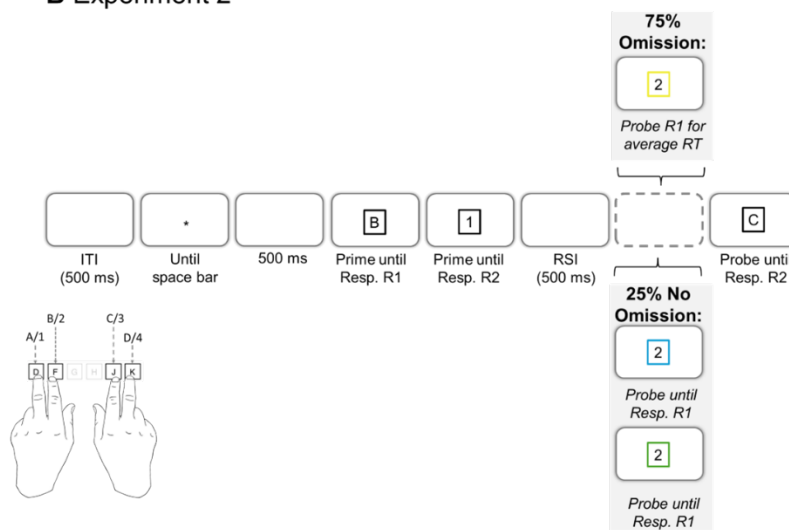
Figure 1

Sequence of Events in One Trial in Experiment 1 and Experiment 2

A Experiment 1



B Experiment 2



Note. Participants responded with their index and middle fingers of both of their hands to the identity of individually presented digits and letters. **A** In Experiment 1, in *probe R1 omission* trials (25% of all trials), a yellow square appearing 250 ms before and subsequently surrounding the probe R1 stimulus cued participants to not execute the probe response R1. In *no omission* trials (75% of all trials; blue, green, or purple square appearing 250 ms before and subsequently surrounding the probe R1 stimulus), participants executed the probe response R1. **B** In Experiment 2, in 75% of all trials (*probe R1 omission* trials), a yellow square cued the participants to not execute the probe response R1. In 25% of all trials (*no omission* trials) a green or blue square surrounding the probe R1 stimulus cued participants to execute the probe response R1. These are examples of a response R1 repetition and response R2 change trial. The asterisk was presented on the screen to indicate that a new trial could be started. Stimuli are not drawn to scale. RSI = response-stimulus interval. ITI = inter-trial interval.

Results

Data processing and analysis were done with R (R Core Team, 2019; R Version 4.3.0). For the analysis of reaction times (RTs), only trials with correct responses R1 and R2 in both prime and probe were included. The rate for at least one error in the prime responses (R1 or R2) was 9.0%. Probe R1 error rate in the probe R1 no omission condition was 4.4%. Probe R2 error rate was 4.2% (only including trials without errors in the previous responses). Additionally, for all analyses, trials in the probe R1 omission condition were excluded if a response was erroneously executed as probe R1 (13.4% of the remaining trials)². RTs that were more than 1.5 interquartile ranges above the third quartile of each participant's RT distribution (Tukey, 1977) and RTs below 200 ms were excluded from the analyses. Due to the exclusion of these responses, 4.1% of the trials were excluded from the RT analyses. For all analyses reported in the following, performance in probe R2 was the dependent variable of interest. If the two responses R1 and R2 in the prime were integrated, repeating prime R1 as probe R1 should trigger retrieval of the second prime response R2, thus influencing probe R2 performance. See **Table 1** for mean RTs and **Table 2** for error rates.

² Note that if only omitted trials with correct stimulus identification (loss: 11.4%) are included in the analyses, the identical pattern of results occurs.

Table 1

Mean reaction times (in ms) for probe responses R2 in Experiment 1, as a function of R1 relation from prime to probe, R2 relation from prime to probe, and omission

| | <i>No Omission</i> | | <i>Probe R1 omission</i> | |
|-------------------|--------------------|----------------------|--------------------------|----------------------|
| | <i>R2 change</i> | <i>R2 repetition</i> | <i>R2 change</i> | <i>R2 repetition</i> |
| R1 change | 557 (71) | 588 (75) | 589 (90) | 592 (77) |
| R1 repetition | 579 (70) | 573 (69) | 581 (78) | 595 (90) |
| R1-Priming Effect | -22 [2] | 15 [3] | 8 [5] | -3 [3] |

Note. Standard deviations in parentheses. Standard error of the mean in squared brackets. R1-priming effect computed as the difference between R1 repetition and change.

Table 2

Mean error rates (in %) for probe responses R2 in Experiment 1, as a function of R1 relation from prime to probe, R2 relation from prime to probe, and omission

| | <i>No Omission</i> | | <i>Probe R1 omission</i> | |
|-------------------|--------------------|----------------------|--------------------------|----------------------|
| | <i>R2 change</i> | <i>R2 repetition</i> | <i>R2 change</i> | <i>R2 repetition</i> |
| R1 change | 3.4 (3.0) | 5.6 (4.5) | 3.2 (4.2) | 4.3 (5.1) |
| R1 repetition | 4.6 (3.5) | 4.7 (4.1) | 3.1 (3.5) | 4.6 (5.4) |
| R1-Priming Effect | -1.2 [0.3] | 0.9 [0.3] | 0.1 [0.5] | -0.4 [0.5] |

Note. Standard deviations in parentheses. Standard error of the mean in squared brackets. R1-priming effect computed as the difference between R1 repetition and change.

Reaction times

A 2 (R1 relation: repetition vs. change) x 2 (R2 relation: repetition vs. change) x 2 (omission: no omission vs. probe R1 omission) repeated measure analysis of variance (ANOVA) on probe R2 RTs yielded a significant two-way interaction between R1 relation and R2 relation, $F(1, 60) = 4.72, p = .034, \eta_p^2 = .07$, indicating a response-response binding effect.

The three-way interaction between R1 relation, R2 relation and omission was significant, $F(1, 60) = 25.31, p < .001, \eta_p^2 = .30$, indicating larger binding effects in the no omission condition (see **Figure 2A**). Post hoc *t*-tests revealed significant response-response binding effects in the no omission condition ($M = 36.37$ ms, $SD = 45.39$ ms, $t(60) = 6.26, p < .001, d_z = 0.80$), but not in the probe R1 omission condition ($M = -11.60$ ms, $SD = 68.38$ ms, $t(60) = -1.33, p = .190, d_z = -0.17$).

For the sake of completeness, the main effect of omission was significant, $F(1,60) = 23.22, p < .001, \eta_p^2 = .30$. Participants responded faster if probe response R1 was executed (no omission condition; $M = 574$ ms, $SD = 72$ ms) than if it was not executed (probe R1 omission condition; $M = 589$ ms, $SD = 81$ ms). Also, the main effect of R2 relation, $F(1,60) = 8.22, p = .006, \eta_p^2 = .12$, was significant. Participants responded faster if response R2 changed from prime to probe ($M = 576$ ms, $SD = 78$ ms) than if it repeated ($M = 587$ ms, $SD = 75$ ms). None of the other effects reached significance, $F_s < 3, p_s > .09, \eta_p^2_s < .05$.

Error Rates

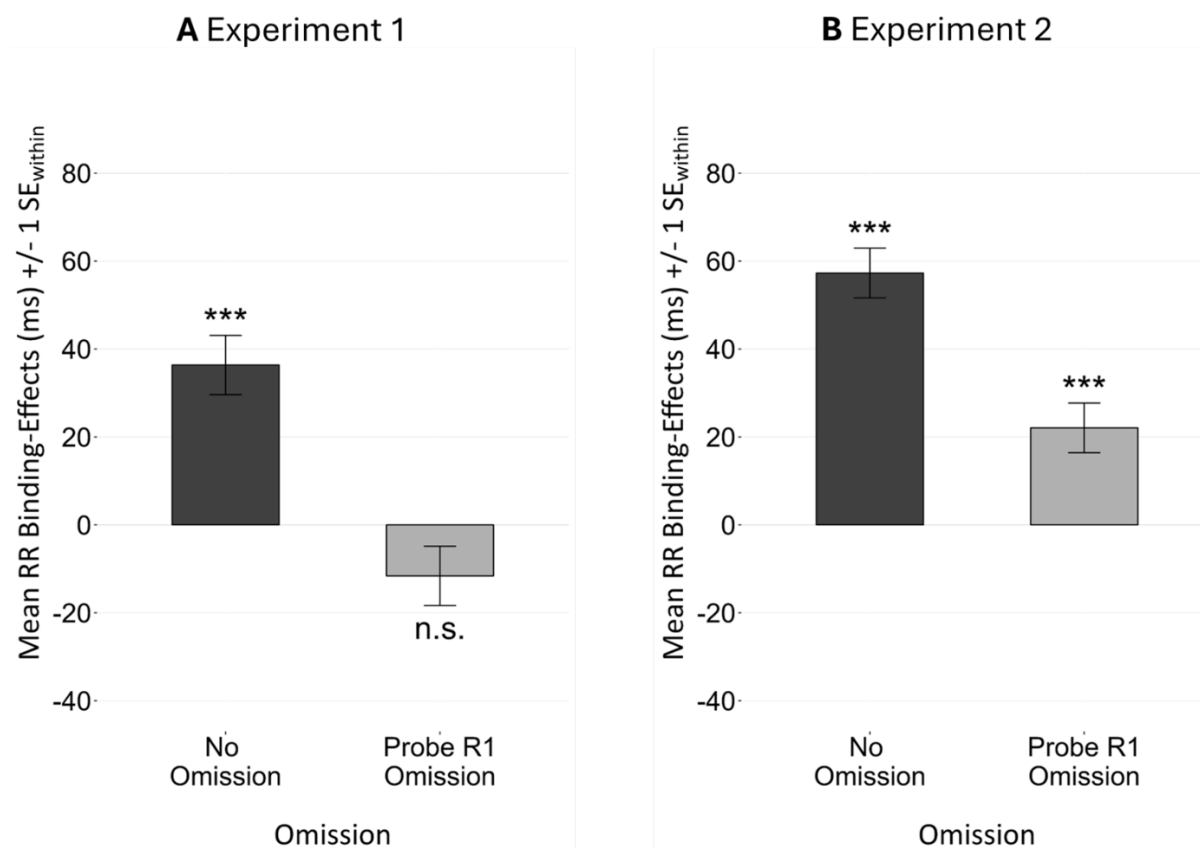
In the same analysis on probe R2 error rates, three-way interaction between R1 relation, R2 relation and omission was significant, $F(1, 60) = 5.47, p = .023, \eta_p^2 = .08$, indicating larger binding effects in the no omission condition. Post hoc *t*-tests revealed significant response-response binding effects in the no omission condition ($M = 2.2\%$, $SD = 2.4\%$, $t(60) = 3.16, p = .002, d_z = 0.40$), but not in the probe R1 omission condition ($M = -0.4\%$, $SD = 0.3\%$, $t(60) = -0.46, p = .644, d_z = -0.06$).

For the sake of completeness, the main effect of omission was significant, $F(1,60) = 5.72, p = .020, \eta_p^2 = .09$. Participants made more errors if probe response R1 was executed (no omission condition; $M = 4.6\%$, $SD = 3.9\%$) than if it was not executed (probe R1 omission condition; $M = 3.8\%$, $SD = 4.6\%$). Also, the main effect of R2 relation was significant, $F(1, 60) = 10.92, p = .002, \eta_p^2 = .15$. Participants made fewer errors if response R2 changed from

prime to probe ($M = 3.6\%$, $SD = 3.6\%$) than if it repeated ($M = 4.8\%$, $SD = 4.8\%$). None of the other effects reached significance, $F_s < 4$, $p_s > .05$, $\eta_p^2_s < .07$.

Figure 2

Binding effects in reaction times as a function of omission (No Omission vs. Probe R1 Omission) in Experiment 1 and Experiment 2



Note. **A** Response–response binding effects in reaction times as a function of omission (no omission vs. probe R1 omission) in Experiment 1. **B** Response–response binding effects in reaction times as a function of omission (no omission vs. probe R1 omission) in Experiment 2. The response–response binding effect was computed 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 ($[R1cR2r-R1rR2r] - [R1cR2c-R1rR2c]$). n.s. = $p > 0.050$, * $p < 0.050$, ** $p < 0.010$, *** $p < 0.001$

Discussion

In Experiment 1, we found strong evidence for binding between responses when the retrieving probe response R1 was executed and thus replicated previous findings on response-

response binding effects. However, no significant response-response binding effects were observed when the retrieving probe response R1 was not executed. In contrast to previous studies demonstrating response-response binding effects even when individual responses were not executed (Nemeth et al., 2024), we here presented the omission cues 250 ms *before* the stimulus that was associated with the to-be-omitted response. Our findings suggest that, for not executed responses, an omission cue followed by merely perceiving and processing a stimulus was not sufficient to trigger the retrieval of the prime event file, thereby resulting in the absence of response-response binding effects. With that, our findings in Experiment 1 are in line with ideomotor approaches such as BRAC by highlighting the critical role of the *intention or goal* to achieve specific action consequences, which acts as a prerequisite for the actual *action planning* of responses and therefore the engagement of responses in binding and retrieval processes.

Experiment 2

In Experiment 2, we focused on the critical role of strategies induced by the experimental context influencing binding and retrieval of responses. Specifically, we investigated a context where the omission of a critical response is the more frequent event than the execution of this response. With such an imbalance a possible strategy would be to refrain from response planning of this response by default. In this case, we would expect no response-response binding effects for omitted responses, similar to what was found in Experiment 1. Instead, a significant response-response binding effect for omitted responses would imply some form of response planning also if such planning was dispensable most of the time.

Method

Participants

The power analysis in Experiment 2 was identical to Experiment 1. 61 participants of Trier University (38 female, 23 male, 56 right-handers) with a median age of 22 years (range:

18–34 years) participated. Participants were recruited via Trier University’s participant platform (Sona Systems; sona-systems.com) and performed the experiment online on the experimental platform Pavlovia (Peirce & MacAskill, 2018). All participants consented via online form before participating and received course credit as compensation. As Experiment 1, this study was done in accordance with the ethics guidelines declared by the ethics committee of Trier University.

Design

The design was the same as in Experiment 1 and included three within-subjects factors: response R1 relation from prime to probe (response repetition vs. response change), response R2 relation from prime to probe (response repetition vs. response change), and omission (no omission vs. probe R1 omission).

Apparatus and Stimulus

Apparatus and Stimuli were the same as in Experiment 1, with the following difference: The outlines of different colored squares (width: 40 pixels, height: 40 pixels) were displayed in black (RGB₂₅₅: 0, 0, 0), yellow (RGB₂₅₅: 255, 255, 0), green (RGB₂₅₅: 0, 128, 0), or blue (RGB₂₅₅: 0, 0, 255) around the stimuli.

Procedure

The procedure was very similar to that in Experiment 1 with the following difference (see **Figure 1B**). Importantly, all squares were exclusively presented simultaneously with the stimuli. In 25% of all trials (omission condition: *no omission*) a blue (50% of the no omission trials) or green (50% of the no omission trials) square surrounded the probe R1 stimulus. These cued the participants to execute their probe response R1. In 75% of the trials (omission condition: *probe R1 omission*) a yellow square surrounded the probe R1 stimulus. Here, participants were cued to not execute their probe response R1.

Results

Data processing and analysis were done with R (R Core Team, 2019; R Version 4.3.0). As in Experiment 1, performance in probe R2 was the dependent variable of interest. For the analysis of reaction times (RTs), only trials with correct responses R1 and R2 in both prime and probe were included. The rate for at least one error in the prime responses (R1 or R2) was 7.2%. Probe R1 error rate in the probe R1 no omission condition was 3.4%. Probe R2 error rate was 4.4% (only including trials without errors in the previous responses). Additionally, for all analyses, trials in the probe R1 omission condition were excluded if a response was erroneously executed as probe R1 (9.6% of the remaining trials). RTs that were more than 1.5 interquartile ranges above the third quartile of each participant's RT distribution (Tukey, 1977) and RTs below 200 ms were excluded from the analyses (4.0%). See **Table 3** for mean RTs and **Table 4** for error rates.

Table 3

Mean reaction times (in ms) for probe responses R2 in Experiment 2, as a function of R1 relation from prime to probe, R2 relation from prime to probe, and omission

| | <i>No Omission</i> | | <i>Probe R1 omission</i> | |
|-------------------|--------------------|----------------------|--------------------------|----------------------|
| | <i>R2 change</i> | <i>R2 repetition</i> | <i>R2 change</i> | <i>R2 repetition</i> |
| R1 change | 592 (88) | 636 (95) | 615 (88) | 651 (92) |
| R1 repetition | 622 (84) | 609 (89) | 633 (89) | 646 (88) |
| R1-priming effect | -30 [3] | 27 [3] | -17 [3] | 5 [2] |

Note. Standard deviations in parentheses. Standard error of the mean in squared brackets. R1-priming effect computed as the difference between R1 repetition and change.

Table 4

Mean error rates (in %) for probe responses R2 in Experiment 2, as a function of R1 relation from prime to probe, R2 relation from prime to probe, and omission

| | <i>No Omission</i> | | <i>Probe R1 omission</i> | |
|-------------------|--------------------|----------------------|--------------------------|----------------------|
| | <i>R2 change</i> | <i>R2 repetition</i> | <i>R2 change</i> | <i>R2 repetition</i> |
| R1 change | 3.0 (4.3) | 6.3 (6.3) | 3.2 (2.4) | 5.6 (4.1) |
| R1 repetition | 5.3 (4.8) | 3.8 (4.1) | 3.8 (3.5) | 4.9 (3.7) |
| R1-Priming Effect | -2.2 [0.5] | 2.5 [0.6] | -0.6 [0.3] | 0.7 [0.4] |

Note. Standard deviations in parentheses. Standard error of the mean in squared brackets. R1-priming effect computed as the difference between R1 repetition and change.

Reaction times

A 2 (R1 relation: repetition vs. change) x 2 (R2 relation: repetition vs. change) x 2 (prime response R2 omission: no omission vs. omission) ANOVA on probe R2 RTs yielded a significant two-way interaction between R1 relation and R2 relation, $F(1, 60) = 77.87, p < .001, \eta_p^2 = .56$, indicating a response-response binding effect. The three-way interaction between R1 relation, R2 relation and omission was significant, $F(1, 60) = 19.44, p < .001, \eta_p^2 = .24$, indicating larger binding effects in the no omission condition (see **Figure 2B**). Post hoc *t*-tests revealed significant response-response binding effects in the no omission condition ($M = 57.29$ ms, $SD = 56.09$ ms, $t(60) = 7.98, p < .001, d_z = 1.02$), but also in the probe R1 omission condition ($M = 22.08$ ms, $SD = 16.64$ ms, $t(60) = 4.85, p < .001, d_z = 0.62$).

For the sake of completeness, the main effect of omission was significant, $F(1,60) = 23.30, p < .001, \eta_p^2 = .28$. Participants responded faster if probe response R1 was executed (no omission condition; $M = 615$ ms, $SD = 90$ ms) than if it was not executed (probe R1 omission condition; $M = 636$ ms, $SD = 90$ ms). Also, the main effect of R1 relation, $F(1,60) = 4.04, p = .049, \eta_p^2 = .06$, was significant. Participants responded faster if response R1 changed from prime to probe ($M = 624$ ms, $SD = 93$ ms) than if it repeated ($M = 628$ ms, $SD = 88$ ms). The main effect of R2 relation, $F(1,60) = 35.07, p < .001, \eta_p^2 = .37$, was significant as well. Participants responded faster if response R2 changed from prime to probe ($M = 616$ ms, $SD =$

88 ms) than if it repeated ($M = 635$ ms, $SD = 92$ ms). Finally, the interaction of R2 relation and omission was significant, $F(1,60) = 5.01$, $p = .029$, $\eta_p^2 = .08$. The interaction of R1 relation and omission was not significant, $F < 2$, $p > .1$, η_p^2 s $< .04$.

Error Rates

In the same analysis on error rates, the interaction between R1 relation and R2 relation was significant, $F(1,60) = 20.98$, $p < .001$, $\eta_p^2 = .26$, indicating response-response binding effects. The three-way interaction between R1 relation, R2 relation and omission was significant as well, $F(1, 60) = 8.94$, $p = .004$, $\eta_p^2 = .13$, indicating larger binding effects in the no omission condition. Post hoc analyses revealed, that the individual response-response binding effects were significantly different from zero for the no omission condition ($M = 4.62\%$, $SD = 5.10\%$, $t(60) = 4.38$, $p < .001$, $d_z = 0.56$) and also for the probe R1 omission condition ($M = 4.37\%$, $SD = 3.60\%$, $t(60) = 2.22$, $p = .030$, $d_z = 0.28$).

For the sake of completeness, the main effect of R2 relation was significant as well, $F(1, 60) = 16.28$, $p < .001$, $\eta_p^2 = .21$. Participants made more errors if response R2 repeated from prime to probe ($M = 5.2\%$, $SD = 4.7\%$) than if it changed ($M = 3.8\%$, $SD = 3.9\%$). None of the other effects reached significance, F s < 2 , p s $> .2$, η_p^2 s $< .03$.

Discussion

In Experiment 2, we found evidence for binding between responses both when the retrieving response was executed and when it was omitted and thus replicated previous findings on response-response binding effects for omitted responses. Notably, we observed response-response binding effects even though the retrieving (probe R1) response was executed in only 25% of the trials. This result pattern indicates that, although the execution of the critical response was a rare event (Geyer et al., 2008), the mere presentation of a stimulus associated with the retrieving response was sufficient to trigger its cognitive representation and therefore event file retrieval. These findings suggest that an experimental context in which the execution

of a specific response is less likely does not induce higher-order strategies that would prevent binding and retrieval processes from operating.

General Discussion

The literature on action control suggests the human cognitive system represents actions through their anticipated sensory consequences rather than through their motor pattern. In line with this assumption, previous studies have shown that individual responses do not have to be executed to be bound into and be retrieved from cognitive representations. However, the conditions under which such binding and retrieval processes operate, particularly in relation to higher-order strategies for action planning, have remained not fully understood. The present work addressed this gap by systematically investigating how the intention to act, certainty about non-execution, and contextual action contingencies shape the binding and retrieval of responses within ongoing action sequences.

Across two experiments, we demonstrated that the current motivation to achieve an action goal modulates binding and retrieval processes when actions are omitted, whereas higher-order strategies induced by the experimental context do not prevent these processes from operating. Importantly, our data show that even intentionally omitted responses can be bound to other responses and can themselves initiate retrieval, dynamics that closely mirror those observed for executed actions. These findings characterize binding and retrieval as surprisingly adaptive, showing that even in the face of uncertainty about action execution within complex sequences, binding and retrieval remain fundamental in facilitating future action taking.

The present study investigated binding and retrieval of individual responses in relation to both the current motivation to achieve a specific action goal (Experiment 1) and higher-order motivation/strategies induced by the experimental context (Experiment 2). To do so, we employed an adapted design that has been demonstrated to reliably test for binding and retrieval

of executed as well as omitted responses (Moeller & Frings, 2019b; Nemeth et al., 2024; see also, Mocke et al., 2024). In Experiment 1, we manipulated the execution (75% of all trials) versus omission of the probe response R1 (25% of all trials) – a manipulation that should target the retrieval of previously bound responses. Crucially, in contrast previous work on response omission (Nemeth et al., 2024), we presented the omission cues 250 ms before the stimulus associated with the to-be-omitted response. This design choice was motivated by the assumption that presenting the omission cue prior to stimulus onset would prevent response planning of the associated (to-be-omitted) response. Thus, by presenting the omission at an earlier point of time than response specifying stimuli, Experiment 1 specifically tested whether binding and retrieval of responses critically depend on the intentional activation of a response goal, rather than on mere stimulus perception.

While our results clearly replicated previous findings on response-response binding effects for executed actions (e.g., Geißler et al., 2021; Moeller et al., 2025; Moeller & Frings, 2019b, 2019d, 2021), response-response binding effects did not emerge when the retrieving probe response R1 was omitted under conditions of early omission certainty. This pattern indicates that mere perception and processing of response-associated stimuli is insufficient for binding and retrieval when action planning is discouraged. Early certainty about non-execution likely prevented the intentional activation of a response goal, thereby eliminating retrieval.

In Experiment 2, we manipulated potential higher-order strategies by making the omission of the probe response R1 the more frequent event (75%) relative to execution (25%). We again observed response-response binding effects for executed actions and, importantly, demonstrated that even under conditions where execution was unlikely, retrieval processes remained operative. Crucially, omitted responses now produced significant binding effects, although these were reliably smaller than those observed for executed responses, a pattern consistent with previous findings (Nemeth et al., 2024).

One plausible explanation for reduced binding effects following omission concerns differences in feature overlap. Executed actions provide additional proximal features (e.g., tactile and proprioceptive feedback) that can serve as retrieval cues, thereby strengthening retrieval and therefore binding effects. When responses are planned but omitted, fewer shared features are available, resulting in weaker (but still reliable) retrieval. This interpretation aligns with evidence that reducing effector overlap diminishes response-response binding (Moeller & Frings, 2019d). Beyond feature overlap, comparator models of action control (e.g., Frith et al., 2000) offer an additional perspective. Discrepancies between anticipated and actual sensory consequences, particularly in cases of omission, may induce internal conflict, interference, or surprise, all of which have been associated with weaker memory encoding, reduced sense of agency, and diminished binding strength (Band et al., 2009; Hon & Yeo, 2021; Mocke et al., 2025). Thus, reduced binding for omitted actions may reflect interference between predicted action effects and experienced non-effects.

A critical theoretical contribution of the present findings concerns the nature of action representations when actions are planned but stopped. Giesen and Rothermund (2014) demonstrated that in a stimulus-response binding task, planned but ultimately stopped (prime) responses led to the retrieval of a global stop-tendency rather than the initially planned response. However, the authors themselves noted that this effect may have been driven by their use of a non-selective stop task, in which participants were instructed to stop any response upon a stop signal, without having to discriminate between specific motor responses (Giesen & Rothermund, 2014). In contrast, our findings together with those of Nemeth et al. (2024) indicate that response-response binding preserves response specificity even when actions are omitted, provided that planning has sufficiently progressed. That is, our data suggest that omitted responses are not represented as generic “no-action” events but rather retain the

identity of the negated response (e.g., “not-left”), consistent with findings on nonaction–effect bindings (Kühn & Brass, 2010; Kühn et al., 2009; Weller et al., 2020).

This distinction highlights the critical role of temporal dynamics in inhibition. When inhibitory signals occur after response selection and planning have begun, specific action representations appear to be preserved and tagged with response-specific stop information (Verbruggen et al., 2005). In contrast, early inhibitory signals encountered before planning may prevent the formation of a differentiated response representation altogether, resulting in global inhibition (Aron, 2011; Giesen & Rothermund, 2014). Our Experiment 1 directly supports this distinction by showing that early omission cues abolish binding and retrieval processes.

More broadly, these findings speak to the remarkable efficiency of the cognitive system in forming event representations based on anticipatory information alone. Action planning rather than execution appears to be the critical prerequisite for establishing memory traces that guide future behavior. This conclusion challenges assumptions that localize feature integration primarily at the execution stage (e.g., Dutzi & Hommel, 2009) and substantially extends previous work that focused on action withholding with later execution (e.g., Moicke et al., 2022; Stoet & Hommel, 1999).

Importantly, goal-directed behavior requires sensitivity to the current value of action outcomes (Balleine & Dickinson, 1998). Our data suggest that the cognitive system selectively invests planning resources only when an action outcome is currently desired. Binding effects for omitted responses emerged only when omission cues coincided with response-associated stimuli, but not when omission certainty preceded stimulus processing. This suggests that the mere perception of a stimulus that cues a response but crucially does not prompt the planning of that action, should not result in feature-overlap costs due to retrieval in a subsequent response – just as we found. That is, the stimulus-preceding cue in our Experiment 1 functioned as an experimental setup that discouraged participants from action planning of the retrieval triggering

response. Although, as Stoet and Hommel (1999) pointed out, we also cannot be sure that this manipulation indeed targeted and prevented the planning of responses, it is clearly unnecessary to plan a response that is either specified at a later moment (as in Stoet and Hommel's, 1999, study) or not executed in the following sequence (as in our case). Taken together, Experiment 1 clearly provides empirical support for the assumption that it is the action planning of responses that leads to their integration and retrieval from event files not just perceiving and processing response-associated stimuli (see Hommel et al., 2001).

Crucially, both TEC (Hommel et al., 2001) and BRAC (Frings et al., 2020) are grounded in the ideomotor assumption that actions are represented in terms of their anticipated effects. A direct and falsifiable implication of this assumption is that if an action is planned but not executed, binding and subsequent retrieval of action features should still occur. The present study directly tested this prediction. Specifically, the absence of response-response binding effects generally following omitted probe responses would have constituted evidence against the assumption that action representations can be formed without action execution. Instead, we observed robust binding effects whenever action planning was likely to occur, even in the absence of execution, thereby providing support for this core assumption. At the same time, the elimination of binding effects when action planning was discouraged demonstrates that binding and retrieval are not inevitable consequences of mere stimulus processing, highlighting a boundary condition of automatic binding and retrieval.

Specifically, the critical role of action planning in binding and retrieval processes raises the question of whether retrieval operates as an automatic process independent of beneficial or hindering consequences for current action (e.g., Mayr & Buchner, 2010), or whether it can be influenced by higher-order strategies. Indeed, it was already demonstrated that experimental contexts influence the extent to which performance is affected by episodic retrieval processes (Frings & Wentura, 2008; Kane et al., 1997; Lowe, 1979). However, crucially, binding and

retrieval effects have been observed even in contexts in which retrieval impedes efficient action regulation (Giesen & Rothermund, 2015). In such studies on stimulus-response bindings, retrieval is typically strengthened in contexts where it is beneficial (i.e., contexts involving more frequent stimulus repetitions than changes), while it is weakened if it more frequently disrupts performance (Kane et al., 1997; Lowe, 1979). Likewise, it could be argued that in Experiment 2 of the present study, action execution versus omission contingencies were manipulated and in cases of omissions, cognitive resources were likely needed to inhibit an already formed action plan (see, Logan & Cowan, 1984). However, since response repetitions and changes were orthogonally varied, retrieval of both omitted and executed responses equally disrupted performance as much as it facilitated it. Thus, in contrast to the previously mentioned studies, our experimental context did not systematically vary the extent to which retrieval affected performance, given that omitting the retrieving response led to both benefits and costs in subsequent performance.

It is important to note that we did not explicitly ask participants whether they developed or used specific strategies due to the experimental context of response omissions. In fact, the cognitive system is tuned to recognize patterns and regularities in the environment (Garner & Felfoldy, 1970), which are assumed to implicitly guide behavior (Reber, 1989). In line with this, stimulus-response binding and retrieval processes have been found to be implicitly modulated by context-dependent contingencies, without any influence of participants' explicit awareness of these contingencies (Giesen & Rothermund, 2015). Thus, our primary interest was not in whether participants developed specific strategies for planning their actions, but rather in whether contingencies that typically make action planning unnecessary also prevent such planning. In this regard, our approach provides a way to test the critical role of forming *intentions* in action control, particularly when uncertainty about executing actions in a sequence may lead to the development of implicit strategies on action planning. In this context, we found

that binding and retrieval acted as robust and protective mechanisms that preserve the integrity of event sequences and facilitate future actions – despite interruptions or intrusions caused by action omissions.

A potential limitation of the present study concerns the constrained randomization inherent to the response-response binding paradigm³. Specifically, the equiprobable realization of the four critical conditions necessarily increases the relative frequency of particular prime-probe relations (i.e., full repetitions), thereby introducing subtle regularities in the response sequence. Such regularities may give rise to a degree of predictability that participants can acquire and may contribute to the overall magnitude of observed binding effects. However, both prior studies and the present data argue against the notion that the present findings can be explained by predictability of response sequences. Specifically, binding effects have been demonstrated under conditions without balanced frequencies (Moeller & Frings, 2019a; Experiment 3), and, in the current experiments, the fastest responses occurred in the full-change condition, which is the least predictable. Moreover, as sequence predictability was constant across our critical manipulation (omission vs. no omission), differences in individual binding effects cannot be attributed to this factor alone. More generally, response-response binding effects are more consistent with transient binding processes than with the acquisition of stable serial-order representations assumed in sequence learning accounts (see Moeller & Frings, 2019c). Nevertheless, the possibility that predictability-related influences contributed to the observed effects cannot be entirely ruled out, and future research may therefore benefit from employing designs that reduce structural regularities while maintaining sufficient statistical sensitivity.

In conclusion, we could demonstrate that binding and retrieval processes are reliable mechanisms that crucially depend on the current intention (Frings et al., 2020; Hommel et al.,

³ We thank an anonymous reviewer for pointing this out.

2001; or put differently, the motivation, e.g., Wit & Dickinson, 2009) to achieve a current action goal, yet remain robust to higher-order strategies induced by the experimental context of action omissions. Taken together, retrieval appears to be a highly adaptive process that operates beyond immediate action contingencies, facilitating efficient action control in future behavior.

Declarations

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Conflict of interest

The authors report no conflict of interest.

Ethics approval

These studies were conducted in accordance with the ethical guidelines defined by the university's ethics committee.

Consent to participate

Informed consent was obtained from all individual participants included in the study.

Consent for publication

Participants have consented to their anonymized data being published in a data repository.

Availability of data and materials

The data of the experiments is available at OSF (https://osf.io/n79hv/?view_only=4016fea6eb29460f90d9a8fdc842ccba). None of the experiments were preregistered.

Code availability

Not applicable.

Authors' contributions

MN: Conceptualization, Data Curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization; Writing - Original Draft, Writing - Review & Editing; **KR:** Conceptualization, Writing - Original Draft, Writing - Review & Editing; **CF:** Conceptualization, Funding acquisition, Resources, Supervision, Writing - Original Draft, Writing - Review & Editing; **BM:** Conceptualization, Funding acquisition, Resources, Supervision, Writing - Original Draft, Writing - Review & Editing.

References

- Allport, A. (1987). Selection for action: Some behavioral and neurophysiological considerations of attention and action. In H. Heuer & A. F. Sanders (Eds.), *Perspectives on Perception and Action* (pp. 395–419). Taylor & Francis.
- Aron, A. R. (2011). From reactive to proactive and selective control: Developing a richer model for stopping inappropriate responses. *Biological Psychiatry*, *69*(12), e55-68. <https://doi.org/10.1016/j.biopsych.2010.07.024>
- Balleine, B. W., & Dickinson, A [A.] (1998). Goal-directed instrumental action: Contingency and incentive learning and their cortical substrates. *Neuropharmacology*, *37*(4-5), 407–419. [https://doi.org/10.1016/s0028-3908\(98\)00033-1](https://doi.org/10.1016/s0028-3908(98)00033-1)
- Band, G. P. H., van Steenbergen, H., Ridderinkhof, K. R., Falkenstein, M., & Hommel, B. (2009). Action-effect negativity: Irrelevant action effects are monitored like relevant feedback. *Biological Psychology*, *82*(3), 211–218. <https://doi.org/10.1016/j.biopsycho.2009.06.011>

- Beste, C., Münchau, A., & Frings, C. (2023). Towards a systematization of brain oscillatory activity in actions. *Communications Biology*, 6(1), 137.
<https://doi.org/10.1038/s42003-023-04531-9>
- Dutzi, I. B., & Hommel, B. (2009). The microgenesis of action-effect binding. *Psychological Research*, 73(3), 425–435. <https://doi.org/10.1007/s00426-008-0161-7>
- Ebbesen, C. L., & Brecht, M. (2017). Motor cortex - to act or not to act? *Nature Reviews Neuroscience*, 18(11), 694–705. <https://doi.org/10.1038/nrn.2017.119>
- Eder, A. B. (2023). A perceptual control theory of emotional action. *Cognition & Emotion*, 37(7), 1167–1184. <https://doi.org/10.1080/02699931.2023.2265234>
- Eder, A. B., Rothermund, K., Houwer, J. de, & Hommel, B. (2015). Directive and incentive functions of affective action consequences: An ideomotor approach. *Psychologische Forschung*, 79(4), 630–649. <https://doi.org/10.1007/s00426-014-0590-4>
- Elsner, B., & Hommel, B. (2001). Effect anticipation and action control. *Journal of Experimental Psychology: Human Perception and Performance*, 27(1), 229–240.
<https://doi.org/10.1037/0096-1523.27.1.229>
- Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, 39(2), 175–191. <https://doi.org/10.3758/bf03193146>
- Filevich, E., Kühn, S., & Haggard, P. (2012). Intentional inhibition in human action: The power of 'no'. *Neuroscience and Biobehavioral Reviews*, 36(4), 1107–1118.
<https://doi.org/10.1016/j.neubiorev.2012.01.006>
- Frings, C., Beste, C., Benini, E., Möller, M., Dignath, D., Giesen, C. G., Hommel, B., Kiesel, A., Koch, I., Kunde, W., Mayr, S., Mocke, V., Moeller, B., Münchau, A., Parmar, J., Pastötter, B., Pfister, R., Philipp, A. M., Qiu, R., . . . Schmalbrock, P.

- (2024). Consensus definitions of perception-action-integration in action control. *Communications Psychology*, 2(1), 1–5. <https://doi.org/10.1038/s44271-023-00050-9>
- Frings, C., Hommel, B., Koch, I., Rothermund, K., Dignath, D., Giesen, C., Kiesel, A., Kunde, W., Mayr, S., Moeller, B., Möller, M., Pfister, R., & Philipp, A. (2020). Binding and Retrieval in Action Control (BRAC). *Trends in Cognitive Sciences*, 24(5), 375–387. <https://doi.org/10.1016/j.tics.2020.02.004>
- Frings, C., Rothermund, K., & Wentura, D. (2007). Distractor repetitions retrieve previous responses to targets. *Quarterly Journal of Experimental Psychology*, 60(10), 1367–1377. <https://doi.org/10.1080/17470210600955645>
- Frings, C., & Wentura, D. (2008). Separating context and trial-by-trial effects in the negative priming paradigm. *European Journal of Cognitive Psychology*, 20(2), 195–210. <https://doi.org/10.1080/17470910701363090>
- Frith, C. D., Blakemore, S. J., & Wolpert, D. M. (2000). Abnormalities in the awareness and control of action. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, 355(1404), 1771–1788. <https://doi.org/10.1098/rstb.2000.0734>
- Garner, W., & Felfoldy, G. L. (1970). Integrality of stimulus dimensions in various types of information processing. *Cognitive Psychology*, 1(3), 225–241. [https://doi.org/10.1016/0010-0285\(70\)90016-2](https://doi.org/10.1016/0010-0285(70)90016-2)
- Geißler, C. F., Frings, C., & Moeller, B. (2021). Illuminating the prefrontal neural correlates of action sequence disassembling in response-response binding. *Scientific Reports*, 11(1), 22856. <https://doi.org/10.1038/s41598-021-02247-6>
- Geyer, T., Müller, H. J., & Krummenacher, J. (2008). Expectancies modulate attentional capture by salient color singletons. *Vision Research*, 48(11), 1315–1326. <https://doi.org/10.1016/j.visres.2008.02.006>

- Giesen, C. G., & Rothermund, K. (2014). You better stop! Binding "stop" tags to irrelevant stimulus features. *Quarterly Journal of Experimental Psychology*, *67*(4), 809–832. <https://doi.org/10.1080/17470218.2013.834372>
- Giesen, C. G., & Rothermund, K. (2015). Adapting to stimulus-response contingencies without noticing them. *Journal of Experimental Psychology: Human Perception and Performance*, *41*(6), 1475–1481. <https://doi.org/10.1037/xhp0000122>
- Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: With special reference to the ideo-motor mechanism. *Psychological Review*, *77*(2), 73–99. <https://doi.org/10.1037/h0028689>
- Henson, R. N., Eckstein, D., Waszak, F., Frings, C., & Horner, A. J. (2014). Stimulus-Response bindings in priming. *Trends in Cognitive Sciences*, *18*(7), 376–384. <https://doi.org/10.1016/j.tics.2014.03.004>
- Herbart, J. F. (1816). *Lehrbuch der Psychologie*. Unzer.
- Herbart, J. F. (1825). *Psychologie als Wissenschaft neu gegründet auf Erfahrung, Metaphysik und Mathematik*. 2. Unzer.
- Herwig, A. (2015). Linking perception and action by structure or process? Toward an integrative perspective. *Neuroscience and Biobehavioral Reviews*, *52*, 105–116. <https://doi.org/10.1016/j.neubiorev.2015.02.013>
- Hommel, B. (2004a). Coloring an action: Intending to produce color events eliminates the Stroop effect. *Psychologische Forschung*, *68*(2-3), 74–90. <https://doi.org/10.1007/s00426-003-0146-5>
- Hommel, B. (2004b). Event files: Feature binding in and across perception and action. *Trends in Cognitive Sciences*, *8*(11), 494–500. <https://doi.org/10.1016/j.tics.2004.08.007>

- Hommel, B. (2013). Ideomotor Action Control: On the Perceptual Grounding of Voluntary Actions and Agents. In W. Prinz, M. Beisert, & A. Herwig (Eds.), *Action Science* (pp. 112–136). MIT Press. <https://doi.org/10.7551/mitpress/9780262018555.003.0005>
- Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The Theory of Event Coding (TEC): A framework for perception and action planning. *Behavioral and Brain Sciences*, 24(5), 849-878. <https://doi.org/10.1017/s0140525x01000103>
- Hon, N., & Yeo, N. (2021). Having a sense of agency can improve memory. *Psychonomic Bulletin & Review*, 28(3), 946–952. <https://doi.org/10.3758/s13423-020-01849-x>
- James, W. (1890). *The principles of psychology, Vol. 2*. Harvard University Press. <https://doi.org/10.1037/10538-000>
- James, W. (1950). *The principles of psychology: Vol. 2*. (Original work published 1890). New York, NY: Dover.
- Janczyk, M., & Kunde, W. (2020). Dual tasking from a goal perspective. *Psychological Review*, 127(6), 1079–1096. <https://doi.org/10.1037/rev0000222>
- Kane, M. J., May, C. P., Hasher, L., Rahhal, T., & Stoltzfus, E. R. (1997). Dual mechanisms of negative priming. *Journal of Experimental Psychology: Human Perception and Performance*, 23, 632–650.
- Konorski, J. (1967). *Integrative activity of the brain*. University of Chicago Press. <https://psycnet.apa.org/record/1967-35012-000>
- Kühn, S., Elsner, B., Prinz, W., & Brass, M. (2009). Busy doing nothing: Evidence for nonaction--effect binding. *Psychonomic Bulletin & Review*, 16(3), 542–549. <https://doi.org/10.3758/PBR.16.3.542>
- Kunde, W. (2001). Response-effect compatibility in manual choice reaction tasks. *Journal of Experimental Psychology: Human Perception and Performance*, 27(2), 387–394. <https://doi.org/10.1037/0096-1523.27.2.387>

- Kunde, W., Koch, I., & Hoffmann, J. (2004). Anticipated action effects affect the selection, initiation, and execution of actions. *The Quarterly Journal of Experimental Psychology Section a*, *57*(1), 87–106. <https://doi.org/10.1080/02724980343000143>
- Laycock, T. (1860). *Mind and Brain: Or, the Correlations of Consciousness and Organisation; with Their Applications to Philosophy, Zoology, Physiology, Mental Pathology, and the Practice of Medicine*. Sutherland & Knox.
<https://doi.org/10.1037/12161-000>
- Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review*, *95*(4), 492–527. <https://doi.org/10.1037/0033-295X.95.4.492>
- Logan, G. D., & Cowan, W. B. (1984). On the ability to inhibit thought and action: A theory of an act of control. *Psychological Review*, *91*(3), 295–327.
<https://doi.org/10.1037//0033-295x.91.3.295>
- Lowe, D. G. (1979). Strategies, context, and the mechanism of response inhibition. *Memory & Cognition*, *7*(5), 382–389. <https://doi.org/10.3758/BF03196943>
- Mayr, S., & Buchner, A. (2010). Episodic retrieval processes take place automatically in auditory negative priming. *European Journal of Cognitive Psychology*, *22*(8), 1192–1221. <https://doi.org/10.1080/09541440903409808>
- Mocke, V., Beste, C., Pastötter, B., & Kunde, W. (2024). Action plan discarding leads to unbinding of action features. *Journal of Experimental Psychology: Human Perception and Performance*, *50*(9), 903–917. <https://doi.org/10.1037/xhp0001219>
- Mocke, V., Holzmann, P., Hommel, B., & Kunde, W. (2022). Beyond Left and Right: Binding and Retrieval of Spatial and Temporal Features of Planned Actions. *Journal of Cognition*, *5*(1), 6. <https://doi.org/10.5334/joc.197>

Mocke, V., Kunde, W., & Schreiner, M. R. (2025). *Compatible Effects Enhance Short-Term Action-Effect Binding*. Center for Open Science.

https://doi.org/10.31219/osf.io/2g36z_v2

Moeller, B., Beste, C., Münchau, A., & Frings, C. (2025). Large scale event segmentation affects the microlevel action control processes. *Journal of Experimental Psychology: General*, *154*(4), 969–979. <https://doi.org/10.1037/xge0001681>

Moeller, B., & Frings, C. (2019a). Binding processes in the control of nonroutine action sequences. *Journal of Experimental Psychology: Human Perception and Performance*, *45*(9), 1135–1145. <https://doi.org/10.1037/xhp0000665>

Moeller, B., & Frings, C. (2019b). From simple to complex actions: Response-response bindings as a new approach to action sequences. *Journal of Experimental Psychology: General*, *148*(1), 174–183. <https://doi.org/10.1037/xge0000483>

Moeller, B., & Frings, C. (2019c). Lost time: Bindings do not represent temporal order information. *Psychonomic Bulletin & Review*, *26*(1), 325–331. <https://doi.org/10.3758/s13423-018-1493-y>

Moeller, B., & Frings, C. (2019d). Response-response binding across effector-set switches. *Psychonomic Bulletin & Review*, *26*(6), 1974–1979. <https://doi.org/10.3758/s13423-019-01669-8>

Moeller, B., & Frings, C. (2021). Remote binding counts: Measuring distractor-response binding effects online. *Psychological Research*, *85*(6), 2249–2255. <https://doi.org/10.1007/s00426-020-01413-1>

Moeller, B., & Pfister, R. (2022). Ideomotor learning: Time to generalize a longstanding principle. *Neuroscience and Biobehavioral Reviews*, *140*, 104782. <https://doi.org/10.1016/j.neubiorev.2022.104782>

- Nemeth, M., Frings, C., Schmalbrock, P., & Moeller, B. (2024). No need to execute: Omitted responses still yield response-response binding effects. *Journal of Experimental Psychology: Human Perception and Performance*, *50*(12), 1196–1205. <https://doi.org/10.1037/xhp0001251>
- Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*(1), 195–203. <https://doi.org/10.3758/s13428-018-01193-y>
- Peirce, J., & MacAskill, M. (2018). *Building experiments in PsychoPy*. SAGE Publications.
- Pezzulo, G., Baldassarre, G., Butz, M. V., Castelfranchi, C., & Hoffmann, J. (2007). From Actions to Goals and Vice-Versa: Theoretical Analysis and Models of the Ideomotor Principle and TOTE. In (pp. 73–93). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-74262-3_5
- Prinz, W. (1997). Perception and Action Planning. *European Journal of Cognitive Psychology*, *9*(2), 129–154. <https://doi.org/10.1080/713752551>
- R Core Team. (2019). *A language and environment for statistical computing*. R Foundation for Statistical Computing. <https://www.R-project.org/>
- Reber, A. S. (1989). Implicit learning and tacit knowledge. *Journal of Experimental Psychology: General*, *118*(3), 219–235. <https://doi.org/10.1037/0096-3445.118.3.219>
- Shin, Y. K., Proctor, R. W., & Capaldi, E. J. (2010). A review of contemporary ideomotor theory. *Psychological Bulletin*, *136*(6), 943–974. <https://doi.org/10.1037/a0020541>
- Stoet, G., & Hommel, B. (1999). Action planning and the temporal binding of response codes. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(6), 1625–1640. <https://doi.org/10.1037/0096-1523.25.6.1625>
- Tukey, J. W. (1977). *Exploratory data analysis*. Addison-Wesley series in behavioral science Quantitative methods. Addison-Wesley.

- Verbruggen, F., Liefoghe, B., & Vandierendonck, A. (2005). On the difference between response inhibition and negative priming: Evidence from simple and selective stopping. *Psychological Research*, 69(4), 262–271. <https://doi.org/10.1007/s00426-004-0177-6>
- Watson, P., Wiers, R. W., Hommel, B., & Wit, S. de (2018). Motivational sensitivity of outcome-response priming: Experimental research and theoretical models. *Psychonomic Bulletin & Review*, 25(6), 2069–2082. <https://doi.org/10.3758/s13423-018-1449-2>
- Wit, S. de, & Dickinson, A [Anthony] (2009). Associative theories of goal-directed behaviour: A case for animal-human translational models. *Psychologische Forschung*, 73(4), 463–476. <https://doi.org/10.1007/s00426-009-0230-6>