Re-visiting an affective modulation of stimulus-response binding and retrieval

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Abstract

Action control theories propose that responding to a stimulus leads to the integration of response and stimulus features into a common representation. Repeating any component can retrieve previously bound information, manifesting in so-called stimulus-response (S-R) binding effects. Previous research suggested that S-R binding may be enhanced by positive compared to negative affect, whereas other studies have found no such modulation. We tested whether this difference might depend on the timing of the affective influence on binding and/or retrieval. In a standard sequential prime-probe paradigm participants were asked to respond to the shape of stimuli presented in the first (prime) trial and the subsequent (probe) trial. From prime to probe, stimuli either repeated or changed their color, which was irrelevant to the shape discrimination tasks, allowing us to assess S-R binding effects between color and response. Between prime and probe displays, we presented positive or negative images, either directly after the prime offset or immediately before the probe onset. In a pre-registered, high-powered experiment (*N* = 134) we found clear evidence for S-R binding effects that were not modulated by the presentation of affective images in either timing condition. The results demonstrate that affective content does not modulate binding and retrieval.

Keywords: Action control; Stimulus-response binding; affect; Attentional disengagement

Every day we interact with our environment. For example, we grab a coffee mug to drink a sip of it or we press the light switch to turn on the light. These simple actions are bodily movements executed with an intention in mind (see Frings et al., 2020; Prinz, 1998). While we execute such actions, we begin to form associations between our movements and the environment (see Logan, 1988). Here, it is reasonable to assume that such actions become more closely connected to the situation if they previously have led to successful or goal-achieving outcomes in this situation ("law of effect", Thorndike, 1911). If we know that pressing a certain light switch turns on the desired light, our action plan of pressing said switch might be reinforced next time we enter the dark room. In contrast, if an action results in a negative outcome or becomes negatively associated – for example, grabbing the coffee mug not at the cold handle but at the hot body – this action plan might be less likely re-used. In short, re-using action plans in a specific situation should be affected by affective associations or consequences, specifically, reinforced if positive and weakened if negative.

Interestingly, modern cognitive theories like the Theory of Event Coding (Hommel, 1998; Hommel et al., 2001) and the Binding and Retrieval in Action Control-framework (BRAC; Beste et al., 2023; Frings et al., 2020, 2024) also claim that mental connections between stimuli (situations) and responses (actions) play a crucial role for action control. Specifically, responding to a stimulus with certain features is assumed to lead to the binding of response and stimulus features into a common representation, that is, an event file (Hommel, 2004). Re-encountering any component of such an event file leads to the retrieval of previously bound information, which has in turn effects on current behavior: Crucially, if information only partially repeats, partial repetition costs emerge. These effects can be measured in the S1R1-S2R2 paradigm (Hommel, 1998), in which a cue – for example, an arrow – indicates to press a left or right key in response (R1) to the appearance of a first stimulus (S1; e.g., a vertical or horizontal bar with a certain color appearing at one of two locations); shortly after, a second stimulus (S2) is presented which demands to discriminate, for example, the color, shape, or location, using the same response keys (R2) (see Hommel, 1998). From R1 to R2 the stimulus properties (i.e., the components of S1 and S2, like color, shape, and so on) are systematically varied, resulting in combinations of full repetitions, partial repetitions and full changes of responses and stimulus features. Alternatively, prime-probe sequences have been used, which consist of a prime display that includes a response-relevant and

-irrelevant feature, followed by a probe display including a response-relevant and -irrelevant feature as well (e.g., Frings et al., 2007; Rothermund et al., 2005). From prime to probe response-relevant and -irrelevant features are orthogonally varied. For example, participants are instructed to indicate the identity of a target letter (e.g., press the f-key for an F and the j-key for a J) that is framed by two distractor letters (Frings et al., 2007). From prime to probe the response-defining target letter can repeat or change and the response-irrelevant distractor letters can repeat or change. In both paradigms, a full repetition of the event perfectly matches the previously bound information, which can be beneficial for responding (e.g., Frings et al., 2007; Singh et al., 2016). However, repeating the response-irrelevant feature but not the response or repeating the response but changing the response-irrelevant feature leads to increased reaction times and/or error rates, because the previous but no longer applicable event file is retrieved. Complete change does not interfere with responding because no information that potentially could interfere is retrieved (Hommel, 1998).

The effects resulting from binding and retrieval have been termed stimulus-response (S-R) binding effects and have been replicated multiple times with a number of response relevant (e.g., color, Hommel, 1998; Schöpper, Hilchey, et al., 2020; shape, Schöpper & Frings, 2022; word meaning, Giesen & Rothermund, 2011; letters, Frings et al., 2007; pitch, Dyson, 2010) and irrelevant (e.g., color, Schöpper & Frings, 2022; location, Schöpper, Hilchey, et al., 2020; pitch, Zmigrod & Hommel, 2009) features. S-R binding effects also have been found to be modulated by bottom-up factors like figure-ground mechanisms (e.g., Frings & Rothermund, 2017), saliency (Schmalbrock et al., 2021), meaningfulness or long-term memory representation (Schöpper et al., 2025; see also Hommel & Colzato, 2009), or stimulus modality (Schöpper & Frings, 2023) as well as top-down factors like attention (e.g., Hommel, 2005; Moeller & Frings, 2014), instructions/task set (Hommel et al., 2014; Memelink & Hommel, 2013), or task type (Schöpper, Hilchey, et al., 2020; Schöpper & Frings, 2022, 2024; see also Huffman et al., 2018). Moreover, in recent years, binding and retrieval have been argued to be two clearly separable processes (Beste et al., 2023; Frings et al., 2020, 2024) that can be investigated individually (e.g., Laub et al., 2018; Schmalbrock & Frings, 2022).

Important to the current study, a modulating role of rewarding or aversive action outcomes has been argued in the context of action control. Analogously to what has been shown in the literature on operant conditioning investigating the law of effect, demonstrating that responses become more strongly (weakly) associated with situations if these responses are followed by positive (negative) consequences, some studies have also found that action-effect binding is strengthened if consistently followed by rewarding (relative to neutral or punishing) action consequences (Eder et al., 2020; Muhle-Karbe & Krebs, 2012). Additionally, even if responses are incorrectly executed, the correct response is bound, suggesting that the cognitive system biases future responding to have a positive outcome (e.g., Foerster et al., 2022, 2023; Parmar et al., 2022; see also Giesen et al., 2017). While these studies do not necessarily reflect binding and retrieval being modulated by affective content (for a discussion, see Parmar & Rothermund, 2024, p. 363), they at least suggest that actions are to some degree susceptible to affective content.

Colzato et al. (2007) were interested in whether the binding mechanism itself can be modulated by affective content. Specifically, they argued that positive affect is linked to an increase in dopamine which in turn should strengthen the binding process (e.g., Ashby et al., 1999; Schnitzler & Gross, 2005). For investigating this, the authors used the S1R1-S2R2 paradigm and asked participants to respond to the second stimulus based on its color, location, and shape (i.e., three different experiments). Crucially, shortly before the presentation of S2, a positive or negative image was presented after a correct response to S1. Whereas in the experiments in which color and location were response-relevant no modulation by affective content emerged, the experiment with shape as the relevant feature of S2 led to the expected pattern: Larger binding effects emerged when a positive image was presented in-between stimuli. The authors mused post-hoc that the identification of an affective image as positive or negative requires extracting and processing shape information and that “processing of valence seems to rely on attention to shape” (p. 445), which would explain why the affective modulation only occurred for shape discrimination but not for the location and color tasks. However, the authors already note that this would be inconsistent with previous findings of automatic extraction of affective information (Le Doux, 1996; Zajonc, 1980). In fact, the idea for such attentional allocation is supported by research showing that attention to certain feature dimensions can lead to stronger binding effects ("intentional weighting", Hommel et al., 2014; Memelink & Hommel, 2013; see also Frings & Moeller, 2014; Singh et al., 2018). However, the prioritized extraction of affective information due to attentional focus on shape remains speculative, as modern studies have shown that task-irrelevant affective stimuli are automatically evaluated as long as sufficient attention is allocated to them (e.g., Spruyt et al., 2012; see also Singh et al., 2018, 2025). Hence, the assumption that shape processing is uniquely, or even exclusively, tied to the automatic evaluation of stimuli is not supported. Given that, the exact settings for finding an affective modulation of binding effects remain unclear.

Yet, in line with the assumption that positive affect strengthens binding, Waszak and Pholulamdeth (2009) found that action episodes resulting in the presentation of a positive image delayed responding more when that episode was retrieved in a new task context compared to episodes associated with a negative image. The authors explained this modulation by affective information with stronger S-R binding in the first task context – which does not match the new task context. However, the experimental design differed significantly from that of Colzato et al. (2007). Waszak and Pholulamdeth (2009) presented affective images directly after each response and retrieval of the S-R episode was cued several trials later and involved a task switch (Koch et al., 2018), which might also have played a role. Thus, both studies might not be fully comparable.

In a recent study, Parmar and Rothermund (2024) were interested in whether affective *consequences* modulate the effects of binding and retrieval. They argued that in the studies of Colzato et al. (2007) and Waszak and Pholulamdeth (2009), a positive or negative image presented after a response might have been perceived as a positive or negative reinforcement. However, Parmar and Rothermund (2024) criticized that the studies of Colzato et al. (2007) and Waszak and Pholulamdeth (2009) came with some methodological issues such as a low overall sample size; this becomes even more relevant as there has been some criticism regarding the stability of reinforcement effects on binding (for a detailed discussion, see Eder et al., 2020).

For additional tests of an emotional modulation of S-R binding effects by affective information, Parmar and Rothermund (2024) conducted a series of high-powered experiments. In these, participants were asked to identify the color of words while the word served as an irrelevant distractor that could repeat or change (see also Rothermund et al., 2005). Each response resulted in a positive, negative, or neutral feedback in shape of a smiley indicating monetary gains (in form of a point system), losses, or nothing. In Experiments 1 and 2 feedback was independent of correct or fast responding, in Experiments 3 and 4 feedback was performance-dependent, and in Experiment 5 feedback was based on reward probability in a free-choice paradigm. While effects of binding and retrieval were found throughout, in none of the experiments these processes were modulated by affective consequence. Parmar and Rothermund (2024) concluded that the findings of Colzato et al. (2007) and Waszak and Pholulamdeth (2009) were either due to procedural differences or reflect that the effects of affective consequences are very fragile, chance findings due to low power, or only found with quite specific experimental setups. A study by Mocke et al. (2025) using a related design also found no evidence for a modulation by affective action consequences.

However, when comparing[1] the study designs of Parmar and Rothermund (2024) and Mocke et al. (2025) with that of Colzato et al. (2007) (see **Table 1**; see also Table 1 in Parmar & Rothermund, 2024), one notices a striking difference in the experimental procedure: the timing of affective information during the response-stimulus-interval (RSI) between the prime and probe displays. To measure S-R binding effects in sequential paradigms there are typically RSIs of at least 500 ms in-between the first and second response (e.g., Frings et al., 2007; Schöpper et al., 2020; see, however, Nemeth et al., in press, for an RSI of 0 ms which still led to an effect). While some binding effects are heavily reduced or absent if RSIs reach about 2,000 ms or more (e.g., Frings, 2011; Hommel & Frings, 2020; Pastötter et al., 2021; Schöpper et al., 2022b), others remain even with longer RSIs (e.g., 3,000 ms, in Schöpper & Frings, 2025, or 6,000 ms in Moeller & Frings, 2021). However, if RSIs are not too extensive, binding effects are typically robust even in the presence of intervening events (Hilchey et al., 2017; Hommel & Frings, 2020). In Parmar and Rothermund (2024) and Mocke et al.'s (2025) studies, this intervening event was the affective consequence presented for 1,000 ms directly after response execution, followed by a period either for 750 ms (Parmar & Rothermund, 2024) or 900-1,000 ms (Mocke et al., 2025) until the next

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[1] Note that Colzato et al. (2007) used a S1R1-S2R2-task whereas Parmar and Rothermund (2024) and Mocke et al. (2025) used a sequential distractor-response binding paradigm. However, binding frameworks (e.g., Frings et al., 2020, 2024) assume that an event file is created with the first response (i.e., the binding process) which is retrieved when executing the second response in both paradigms. Therefore, both paradigms should produce comparable findings regarding an affective modulation of binding and retrieval.

response-defining target. In contrast, in Colzato et al. (2007) presented the affective image after response execution with a delay of 1000 ms after the first response and *immediately* (200 ms) before the response-defining second stimulus. In case of Parmar and Rothermund (2024) and Mocke et al. (2025), the affective consequence directly happens after response execution, suggesting that it becomes (theoretically) associated with binding of event file information. Although Colzato et al. (2007) interpret their findings as being a binding modulation as well, the pattern could also reflect a modulation of the retrieval process, due to its temporal proximity to the execution of the second response.

Table 1

Overview of previous studies investigating affective consequences

Study	N	Paradigm and task	Placing of affective content	Outcome and interpretation	Further information
Colzato et al. (2007)	N = 23 (Exp. 1) N = 23 (Exp. 2) N = 22 (Exp. 3)	S1R1-S2R2-task with first response being based a cue and second response being based on discriminating the shape (Exp. 1), location (Exp. 2), and color (Exp. 3)	Before second response	Binding effects are increased for positive images in the shape discrimination task (Exp. 1) No modulations in the color and location discrimination tasks (Exp. 1 & 2)	Positive and negative images as affective stimuli Affective consequences response-independent
Parmar & Rothermund (2024)	N = 86 (Exp. 1) N = 78 (Exp. 2) N = 79 (Exp. 3) N = 86 (Exp. 4) N = 137 (Exp. 5)	Sequential distractor-response binding with responses being based on color discrimination	After first response	Binding effects are not modulated by affective content	Positive, neutral, or negative emojis signaling monetary gains or losses as affective stimuli Affective consequences response-independent (Exp. 1 and 2) or response-dependent (Exp. 3 and 4) Experiment 5 combined with instrumental learning
Mocke et al. (2025)	N = 90 (Exp. 1) N = 90 (Exp. 2)	Sequential distractor-response binding with responses being based on color discrimination	After first response	Binding effects are not modulated by affective content	Positive or negative emoji with corresponding sound that signaled monetary gains or losses as affective stimuli Affective consequences response-independent; valence already announced at the beginning of each trial

Why would affective content modulate specifically the retrieval process? Negative emotional information has been found to trigger a temporary “freezing” response (Algom et al., 2004; Roelofs, 2017) and task-irrelevant negative images have been found to cause distraction, disturbing performance (e.g., Augst et al., 2014; Melcher et al., 2011). While negative or threat-related stimuli initially typically attract attention (e.g., spiders; Mogg & Bradley, 2006; Schöpper, Küpper, & Frings, 2023; for reviews, see Clarke et al., 2013, and Vuilleumier, 2005; see, however, Chajut et al., 2010) this pattern is often followed by avoidance (e.g., Koster et al., 2006; Pflugshaupt et al., 2005; Rinck & Becker, 2006); however, attentional disengagement from threatening content[2] might be delayed (e.g., Georgiou et al., 2005; Gerdes et al., 2009). Thus, it is possible that negative images in Colzato et al. (2007) grabbed attention (see also De Houwer & Tibboel, 2010; Öhman et al., 2001) and that it was harder to disengage from these; these occupied attentional resources were then unavailable for the retrieval process, thus reducing the observed effect[3]. Attention has been found to modulate binding effects (e.g., Singh et al., 2018, 2025; see also Memelink & Hommel, 2013). In fact, while attention might not be that relevant for binding of event file information (Hommel, 2005; see also Giesen et al., 2012), retrieval can be heavily modulated by attention: For example, Moeller and Frings (2014) found that response-irrelevant distractors only retrieve previous responses if attention has been allocated to them; if they are unattended, retrieval is reduced or completely abolished. Thus, if attention was distracted or occupied by a previous stimulus, this might – to some degree – reduce the attentional resources needed for retrieving the past event file.

The absent modulations in Parmar and Rothermund (2024) and Mocke et al. (2025) would be in line with this account, due to eased attentional disengagement from threatening content which in turn no longer “prioritizes” information for retrieval: Machado-Pinheiro et al. (2013)

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[2] Note that positive images have been found to also attract attention (Pool et al., 2016) and that reward-associated stimuli also delay disengagement (Watson et al., 2020). In general, emotional stimuli seem to attract attention (e.g., Vuilleumier, 2005).

[3] Schöpper, Küpper, and Frings (2023) investigated a similar mechanism, yet reversing the idea. In their study, they asked participants to discriminate the orientation of bars repeating or changing their location. Crucially, immediately before probe onset they presented an image of a spider and a baby animal, one of which congruent with the following probe location. Increasing attention to a location should increase the retrieval thereof. While they observed an attentional bias towards the position of the spider, this attentional allocation did not modulate measured binding effects. Of note, in their study, positive and negative were always presented simultaneously, potentially balancing each other out (for a discussion, see Schöpper, Küpper, & Frings, 2023, p. 142).

found that participants executed saccades to peripheral targets faster when immediately before that a neutral compared to unpleasant image was presented, suggesting that it was harder to disengage from the latter. However, when there was a stimulus-onset-interval of 200 ms in-between image and peripheral target, saccades were executed faster after unpleasant images compared to neutral ones, suggesting that image offset eased disengagement. As Parmar and Rothermund (2024) and Mocke et al. (2025) always had an interval in-between affective information and target, this might have eliminated attentional resources dwelling on negative content. By that, these attentional resources were no longer occupied, reducing an impact on attention on retrieval.

The occupation of resources by negative affect has been used to explain the observed performance impairments in various paradigms such as spatial working memory tasks (e.g., Gokce et al., 2021; Li et al., 2006, 2010) and auditory oddball discrimination tasks (e.g., Meinhardt & Pekrun, 2010). While memory for negative stimuli might be increased (Kensinger, 2009), negative content can also disrupt memory retrieval of contextual information and/or other (neutral) stimuli (Bisby et al., 2018). This suggests, that negative affect might impair retrieval in sequential trial sequences as measured in binding and retrieval frameworks as well.

A retrieval modulation by affect would also be in line with ideas of correct feedback being perceived as rewarding (Eder & Dignath, 2014; see also Miltner et al., 1997). A positive outcome (i.e., the absence of an error feedback) could become bound to the response/distractor after pressing the correct key in a task. Presenting a positive image – for example, a cute puppy – prior to probe onset might retrieve the positive feedback/reward of absent error feedback. However, presenting a negative image – for example, an attacking snake – close to probe onset might be perceived as a valence change – in other words, when a negative image is presented S-R binding effects are additionally impacted by a valence change which undermines retrieval effects of valence as a feature (Mocke et al., 2025). As most experimental designs investigating binding and retrieval use paradigms in which accuracy rates are far above 80% (e.g., Frings et al., 2007; Hommel, 1998; Schöpper & Frings, 2022; see, however, e.g., Foerster a et al., 2022; Parmar et al., 2022), it is theoretically way more common that positive reward of absent error feedback gets bound to the prime response. This would suggest that affect is not only involved in binary bindings of valence with specific stimulus features or responses (e.g., Schöpper, Jerusalem, et al., 2023; Singh et al., 2018) but that affect serves as a feature that modulates binary bindings between other features/responses: Simply stated, binding effects between two features increase if a third feature (in this case positive valence) repeats (e.g., Hilchey et al., 2018; Moeller et al., 2019). However, we remain agnostic if every correctly-executed response is perceived as rewarding as perceiving a positive image; we thus will speak of images having positive or negative valence in the following.

To summarize, negative affect could reduce binding effects due to occupying attentional resources, imparing working memory, or due to being processed as a feature switch. This suggests that positive affect would not increase binding effects, but that negative affect decreases binding effects. Note that by that, these explanations deviate from that of Colzato et al. (2007), who argued that positive affect increases dopamine levels which in turn increases the strength of binding[4]. We thus hypothesize that the binding process is rather automatic and generally unaffected by an affective modulation, whereas the retrieval process might be prone to an affective modulation due to negative affect impairing performance.

Current study

In the current study we were interested in whether affective pictorial content modulates S-R binding effects – however, not as a form of response feedback that increases or decreases the strength of binding of previous information, but rather as a stimulus that drives the retrieval of such previously bound information. A standard sequential prime-probe paradigm was used to investigate binding and retrieval effects (Frings et al., 2020). Specifically, participants were asked to identify the shape of stimuli in each trial of the task. To do so, they pressed specific keys depending on the shape identity in the prime display and again in the subsequent probe display. The color of these shapes varied orthogonally, either repeating or changing from prime to probe, and served as a response-irrelevant distractor feature. We expected that the response-irrelevant

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[4] Colzato et al. (2007) did not specifically disentangle if they observed an increased S-R binding effect due to positive images or a decreased effect due to negative images; intriguingly, however, they found an impairment of response repetitions after negative images in their shape discrimination task, which might reflect freezing or distraction caused by negative content.

color of the prime stimulus would become bound to the prime response. Accordingly, if the color repeated in the probe, the color information was assumed to automatically retrieve the bound response, thereby facilitating response selection when the response was also repeated in the probe trial but interfering with response selection when the response had changed. Conversely, when the color changed, switching to a different response was expected to be beneficial, as there would be no interference from the retrieval of a now incorrect response. These would reflect a standard effect of binding and retrieval in a shape discrimination task with color as distractor feature (e.g., Hommel, 1998, 2004; Schöpper & Frings, 2022). Additionally, we presented positive and negative images between prime and probe stimuli, independently of response performance. Crucially, in one block the affective image was presented immediately after the execution of the response in the prime display (prime-offset condition), whereas in another block the affective image was presented 500-700 ms after the prime response and immediately prior to probe onset (probe-onset condition). Consistent with the research of Parmar and Rothermund (2024) and Mocke et al. (2025), we would expect no modulation of the S-R binding effect by affective content in the prime-offset condition. In contrast, we would expect S-R binding effects to be modulated by affective content in the probe-onset condition, supporting the study of Colzato et al. (2007).

The studies of Parmar and Rothermund (2024), Mocke et al. (2025), and Colzato et al. (2007) also differ in the way stimuli are mapped to responses. Whereas in Parmar and Rothermund (2024) and Mocke et al. (2025), response repetitions came with target repetitions, the design of Colzato et al. (2007) originates from Hommel (1998) and does not confound this factor as in that paradigm the first response is based on a cue orthogonal to the appearance of S1 (note, however, that by that occasional cue-stimulus incompatibility is inherent to the design). We decided to introduce a distractor-response binding paradigm in which response repetitions could come with or without target repetitions (e.g., Giesen & Rothermund, 2014; Schöpper, Singh, & Frings, 2020; Singh et al., 2016) to control for this factor.

Lastly, Colzato et al. (2007) only used positive and negative images; while the effects are interpreted as binding being improved for positive images, this theoretically could also reflect a decrease of binding with negative images. Parmar and Rothermund (2024) tackled this by introducing a neutral condition. However, we decided to only use positive and negative images as all relevant studies used these categories (see Table 1) as well as to have more power for the effect of interest – the differing impact of positive versus negative affect on action control processes.

Method

Data collection was done in two waves, with the first wave being preregistered at https://aspredicted.org/xn6w-gjn3.pdf and the second wave being preregistered at https://aspredicted.org/dhjd-xzqt.pdf.

Sample

Colzato et al. (2007) observed an effect size of $dz = 0.53$ with $n = 23$ participants for the modulation of a binding pattern by valence. In a first wave, we collected data for 70 participants. With an assumed $\alpha = .05$ (one-tailed) and expected effect size of at least $d = 0.4$, this sample size leads to a power of $1 - \beta = 0.95$ (G*Power, version 3.1.9.7; Faul et al., 2007). In this first wave we exploratively observed an affective modulation of binding effects by response repetitions occurring with or without target repetition. This explorative analysis was preregistered for a second wave of data collection with 70 participants. However, the target-effect did not replicate in the second wave. Given the mixed evidence regarding the reliability of affective modulations of binding and/or retrieval, we decided to collapse both data sets as both were identical in procedure. Thus, a total of 140 students from the University of Trier gathered in two collection waves took part in the experiment for partial course credit; with the above settings, this sample size leads to a power of $1 - \beta > 0.99$. The experiment complied with ethical standards for conducting behavioral studies at University of Trier. Participants gave consent to a linked consent form by clicking a pop-up text field. Prior to experimental start, they were informed that images with negative content would be presented during the course of the experiment. Six participants were excluded from the analysis. Three had only a few trials included for analysis both in reaction times and error rates due to excessive errors made. The other three were heavy outliers in reaction times, errors made, and/or trials excluded from analysis. After exclusion, the final sample consisted of 134 participants (108 female, 25 male, 1 other; $M_{Age} = 21.60$, $SD_{Age} = 3.05$, age range: 18-40 years). Two participants stated that they had uncorrected visual impairments, and five others reported color vision deficiency. As the data from these participants were inconspicuous when compared with the sample, they were included in the analysis. All other subjects reported normal or corrected-to-normal vision.

Design

The experiment used a 2 (valence: positive vs. negative) x 2 (temporal presentation: prime offset vs. probe onset) x 2 (response: repetition vs. change) x 2 (color: repetition vs. change) within-subjects design. A binding effect is derived from the interaction of response and color. This effect can be further modulated by valence and/or temporal presentation.

Apparatus and materials

The experiment was an online study programmed in PsychoPy (Peirce et al., 2019) and hosted online via Pavlovia (https://pavlovia.org/). Due to the online setup, exact sizes of stimuli could vary; however, all stimuli, distances, and positions were programmed in pixels so that the relative sizes were identical, irrespective of the device used. The experiment used a white fixation cross (30 x 30 pixels) on black background. The target (50 x 50 pixels) was shaped as a circle, cross, triangle, or diamond. The color of each shape was red (R/G/B: 237/28/36) or blue (R/G/B: 0/162/232). Affective stimuli were selected from the Geneva Affective Picture Database (GAPED; Dan-Glauser & Scherer, 2011): 24 pictures were used as positive and 24 as negative stimuli[5]. Positive images depicted smiling babies, landscape photographs, as well as different animals (e.g., puppies, kittens, a panda bear, etc.). Negative images depicted starving, mistreated, and/or captively held animals, hunters with trophies, snakes, spiders, as well as humans in difficult situations. Dan-Glauser and Scherer (2011) report valence and arousal ratings for all their images on a scale of 1-100 (valence: 1 = negative, 100 = positive; arousal: 1 = low arousal, 100 = high arousal). In our selection of images, the negative stimuli had an average valence rating of 22.54

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[5] Picture IDs for positive images in Dan-Glauser and Scherer (2011) were: P001, P003, P018, P025, P035, P037, P055, P056, P061, P066, P067, P073, P078, P080, P081, P082, P091, P095, P096, P098, P101, P114, P122, and P128. The IDs for negative images were: A006, A017, A021, A051, A057, A062, A079, A085, A127, A131, H092, H107, Sn011, Sn068, Sn112, Sn131, Sp012, Sp023, Sp033, Sp041, Sp052, Sp112, Sp136, and Sp146.

and the positive stimuli of 91.20. In terms of arousal, the selected negative images had a rating of 62.51 and the positive images had a rating of 19.74. However, we did not control for arousal, as this link between negative images being more arousing than positive stimuli has been observed regularly (e.g., Kuppens et al., 2013) and a previous study showed that the arousal value of stimuli reacted to does not affect binding and retrieval processes (Giesen & Eder, 2022). Images subtended an area of 400 (width) x 300 (height) pixels on the screen.

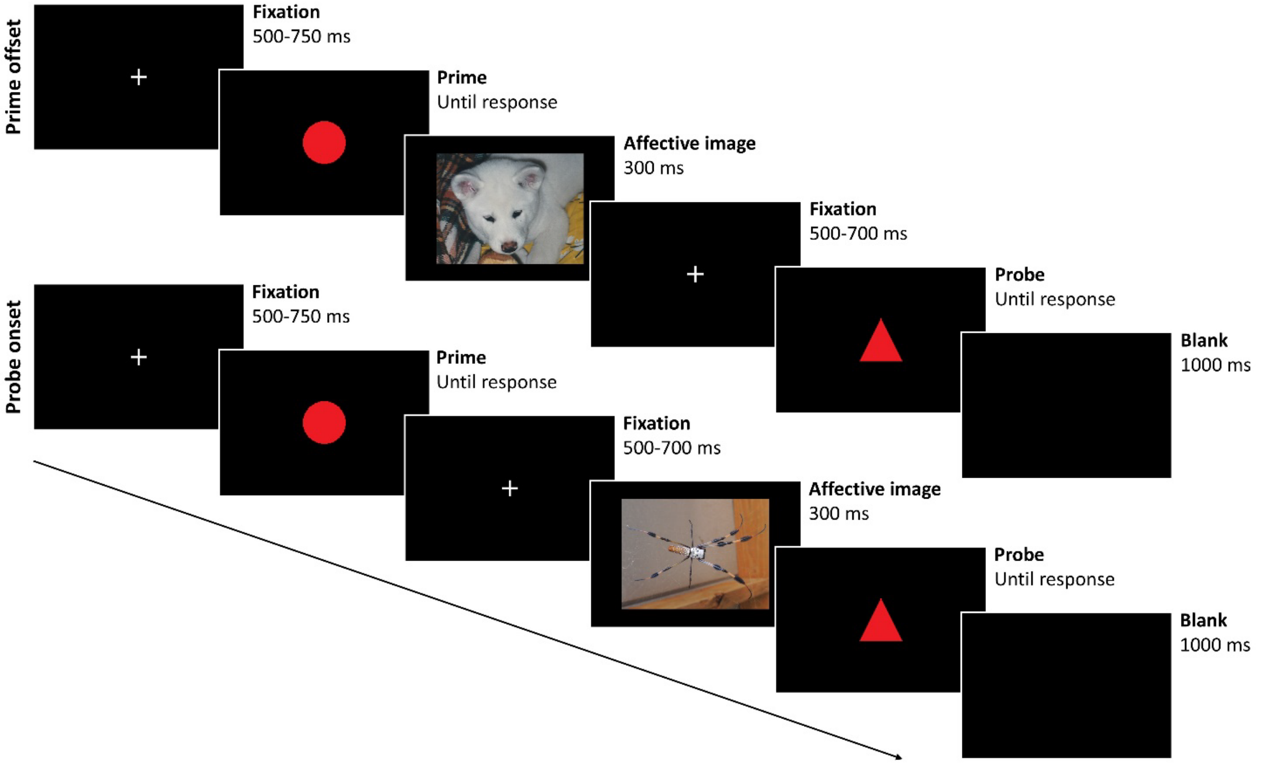
Procedure

The experiment was an online study so individual settings may have varied; however, participants were asked to participate only via laptop/computer and not via smartphone or tablet. Participants performed both temporal presentation blocks; one half started with the prime offset block, the other started with the probe onset block. Both orders were hosted as separate experiments on https://www.sona-systems.com/ and participants could register for one of the two.

The procedure followed a prime-probe structure (**Figure 1**), where participants first respond to a prime display followed by a probe display. Each trial started with a fixation cross in the center of the screen for 500-750 ms. In the following prime display, a colored shape appeared. Participants were instructed to respond to a circle or a cross target by pressing the F-key with their left index finger and to a triangle or a diamond target with the J-key with their right index finger. The shape could be red or blue which was irrelevant for responding. The prime display was visible until response. After prime response execution, the sequence varied depending on temporal presentation block. In the prime offset block the positive or negative image directly appeared for 300 ms at screen center. This was followed by a fixation interval of 500-700 ms. In the probe onset block the fixation interval of 500-700 ms directly followed prime response execution. The positive or negative image then appeared for 300 ms at screen center. Next, the probe display showed a colored target stimulus at screen center which demanded to respond as described for the prime display. After probe response execution, the screen turned blank for 1000 ms until the next trial began with the fixation cross. If participants responded incorrectly during the prime or probe display, an error message appeared for 1,000 ms after the respective response.

Figure 1

Trial sequences as used in the experiment



Note. This figure depicts two possible trial sequences (not drawn-to-scale). Both rows show a response change with the color repeating. The upper row depicts a positive trial in the prime offset condition, the lower row depicts a negative trial in the probe onset condition. The prime offset condition and the probe onset condition were presented block-wise and the order was balanced across participants. Photographs (by the first author) of animals are only used for illustration; the experiment used 48 images of Dan-Glauser and Scherer (2011).

From prime to probe the response could repeat (response repetition, RR) or change (response change, RC) and the color could repeat (color repetition, CR) or change (color change, CC). These were orthogonally varied, resulting in four possible combinations of response and color relation (RRCR, RRCC, RCCR, RCCC). As there were always two shapes mapped to one key, response repetitions could repeat with the target repeating or with the target changing. During a prime-probe sequence a positive or negative image appeared. Depending on the picture valence, a specific image was randomly selected from the respective list of 24 possible images. All combinations of shapes, colors, and valence were pseudo-randomly balanced. Conditions were drawn randomly. These settings were identical for both temporal presentation blocks.

Before each temporal presentation block, participants completed 16 practice trials randomly selected from the list of possible trial combinations. This was followed by 256 experimental trials for each temporal presentation block. This resulted in a total of 32 practice trials and 512 experimental trials. During practice blocks, participants received feedback for 1,000 ms after each response as to whether it was correct or incorrect. In the experimental blocks, feedback was only given after incorrect trials. After every 64th experimental trial, participants could take a self-paced break.

Results

Reaction times

Only trials above 200 ms or below 1.5 interquartile range above the third quartile of a participant's distribution (Tukey, 1977) were included for analysis. Probe reaction times were only analyzed when both prime and probe response were correct. Due to these criteria, 16.72 % of trials were excluded. Practice trials were dropped from analysis.

We performed a 2 (Valence: Positive vs. Negative) x 2 (Temporal presentation: Prime offset vs. Probe onset) x 2 (Response relation: Repetition vs. Change) x 2 (Color relation: Repetition vs. Change) repeated-measures ANOVA on probe reaction times[6]. There was a main effect of valence, $F(1, 133) = 23.28$, $p < .001$, $\eta_p^2 = .15$. Participants were slower in trials with negative (567 ms) compared to positive (562 ms) images. There was also a main effect of temporal presentation, $F(1, 133) = 61.24$, $p < .001$, $\eta_p^2 = .32$. Participants were slower in the probe onset (577 ms) compared

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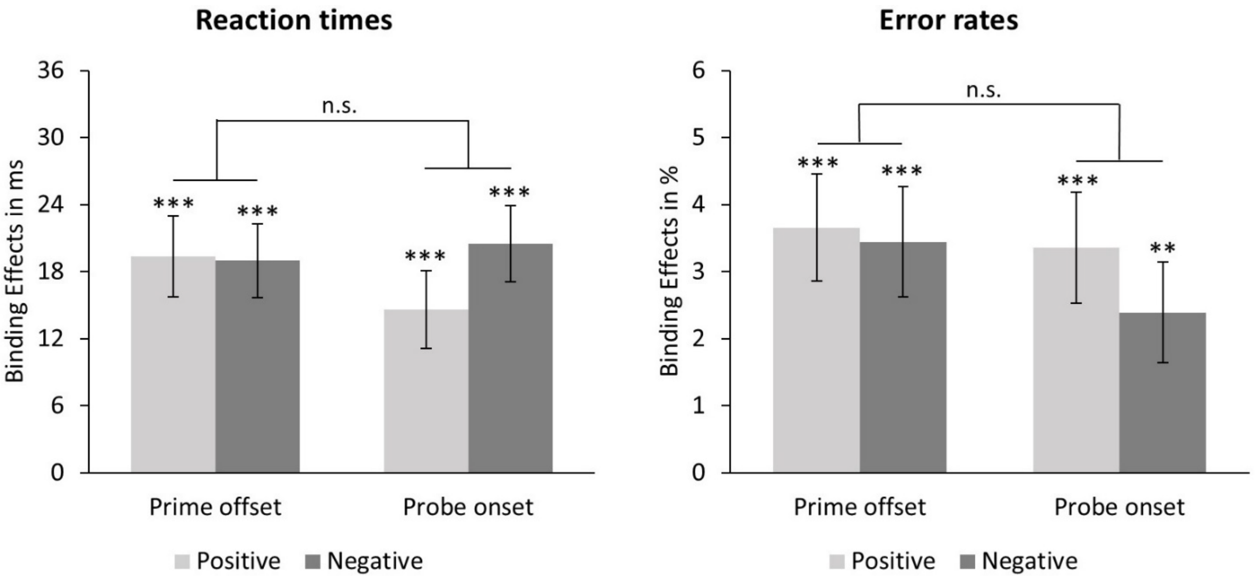
[6] For sake of completeness, we added experimental wave (1 vs. 2) as a between-subject factor to the design. The interaction of experimental wave and temporal presentation block did not reach significance, $F(1, 132) = 3.60$, $p = .060$, $\eta_p^2 = .03$. There was no main effect of wave nor did it modulate any other effects (all $F \leq 0.95$; all $p \geq .331$). When analyzing both waves separately, the interaction of response relation and color relation was significant in both wave 1, $F(1, 66) = 46.74$, $p < .001$, $\eta_p^2 = .42$, and wave 2, $F(1, 66) = 49.53$, $p < .001$, $\eta_p^2 = .43$. However, this interaction was not further modulated by valence and/or temporal presentation block in either wave 1 (all $F \leq 1.32$; all $p \geq .255$) or wave 2 (all $F \leq 0.88$; all $p \geq .352$).

to prime offset (552 ms) block. Lastly, the main effects of response relation, *F*(1, 133) = 169.50, $p < .001$, $\eta_p^2 = .56$, and color relation, *F*(1, 133) = 15.58, $p < .001$, $\eta_p^2 = .11$, were significant: Participants were faster when the response repeated (552 ms) compared to changed (577 ms) as well as faster when the color repeated (563 ms) compared to changed (566 ms). Valence did not interact with the response, *F*(1, 133) = 0.65, $p = .421$, $\eta_p^2 = .01$, or the color, *F*(1, 133) = 0.01, $p = .927$, $\eta_p^2 = .00$. However, valence and temporal presentation interacted, *F*(1, 133) = 13.83, $p < .001$, $\eta_p^2 = .09$: In the prime offset block, participants were about equally fast for positive (552 ms) and negative (553 ms) images. In the probe onset block, participants were slowed by negative (581 ms) compared to positive (573 ms) images. Temporal presentation did not interact with color relation, *F*(1, 133) = 1.85, $p = .176$, $\eta_p^2 = .01$, but with response relation, *F*(1, 133) = 28.36, $p < .001$, $\eta_p^2 = .18$: The response repetition benefit was more pronounced in the prime offset block (RR: 537 ms; RC: 568 ms) compared to the probe onset block (RR: 567 ms; RC: 586 ms). Importantly, response relation and color relation interacted, *F*(1, 133) = 96.60, $p < .001$, $\eta_p^2 = .42$, depicting a standard response retrieval effect: Response repetitions were facilitated by repeating the color (546 ms) compared to changing the color (558 ms), whereas response changes were slowed by repeating (580 ms) compared to changing the color (574 ms). However, this binding effect was not further modulated by valence, *F*(1, 133) = 0.57, $p = .450$, $\eta_p^2 < .01$, or by valence and temporal presentation block, *F*(1, 133) = 0.85, $p = .360$, $\eta_p^2 = .01$. All remaining interactions were not significant (all $F \leq 0.30$; all $p \geq .585$).

To visualize the non-significant interaction, we calculated binding effects as difference scores by (RRCC-RRCR)-(RCCC-RCCR). This calculation sums up the partial repetition costs emerging for response repetitions and changes (e.g., Schöpper & Frings, 2022). These effects are depicted in **Figure 2** (left panel). In the prime-offset block, the binding effect for positive images was 19 ms and significant when tested against zero, *t*(133) = 5.35, $p < .001$, $d = 0.46$, and the binding effect for negative images was 19 ms and significant when tested against zero, t(133) = 5.78, $p < .001$, $d = 0.50$. In the probe-onset block, the binding effect for positive images was 15 ms and significant when tested against zero, t(133) = 4.20, $p < .001$, $d = 0.36$, and the binding effect for negative images was 20 ms and significant when tested against zero, t(133) = 5.99, $p < .001$, $d = 0.52$. As suggested by the non-significant four-way interaction, these effects were not modulated by valence and temporal presentation block.

Figure 2

Calculated binding effects of response relation x color relation, separate for valence and temporal presentation block in reaction times and error rates



*Note. All calculated binding effects of response relation x color relation are significant when individually tested against zero. However, comparing binding effects calculated with positive and negative valence at different temporal presentations is not significant. Error bars depict standard errors of the mean. *** p < .001, ** p < .01, n.s. = not significant*

Error rates

Error rates are the percentage of incorrect probe responses after correct prime responses. Due to that we excluded all trials with incorrect prime responses; by that, 6.57 % of trials were excluded.

We performed the same 2 (Valence: Positive vs. Negative) x 2 (Temporal presentation: Prime offset vs. Probe onset) x 2 (Response relation: Repetition vs. Change) x 2 (Color relation:

Repetition vs. Change) repeated-measures ANOVA on probe error rates[7]. There were main effects of response relation, $F(1, 133) = 10.86$, $p = .001$, $\eta_p^2 = .08$, and color relation, $F(1, 133) = 6.60$, $p = .011$, $\eta_p^2 = .05$, however, in contrast to reaction times depicting more errors for repetitions (RR: 6.63 %; RC: 5.58 %; CR: 6.34 %; CC: 5.88 %). Response relation and color relation interacted, $F(1, 133) = 51.70$, $p < .001$, $\eta_p^2 = .28$, featuring a binding pattern (RRCR: 6.11 %; RRCC: 7.09 %; RCCR: 6.29 %; RCCC: 4.17 %). This binding effect was not further modulated by valence, $F(1, 133) = 0.72$, $p = .398$, $\eta_p^2 = .01$, or by valence and temporal presentation block, $F(1, 133) = 0.234$, $p = .629$, $\eta_p^2 < .01$. All remaining main effects and interactions were not significant (all $F \leq 1.45$; all $p \geq .231$).

The calculated binding effects are depicted in **Figure 2** (right panel). In the prime offset block, the binding effect for positive images was 3.66 % and significant when tested against zero, $t(133) = 4.58$, $p < .001$, $d = 0.40$, and the binding effect for negative images was 3.44 % and significant when tested against zero, t(133) = 4.18, $p < .001$, $d = 0.36$. In the probe onset block, the binding effect for positive images was 3.36 % and significant when tested against zero, t(133) = 4.04, $p < .001$, $d = 0.35$, and the binding effect for negative images was 2.39 % and significant when tested against zero, t(133) = 3.20, $p = .002$, $d = 0.28$. As suggested by the four-way interaction, these effects were not modulated by valence and temporal presentation block.

Explorative analyses

To better compare our results with previous research as well as following our pre-registered analysis, we exploratively looked at the impact of having targets repeat or change in response repetitions and changes as well as potential order effects. However, none of these modulated the (non-significant) impact of valence and temporal presentation on calculated binding effects. The detailed analyses are reported in **Appendix A1**.

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[7] The interaction of experimental wave, temporal presentation block, and response relation was significant, $F(1, 132) = 7.29$, $p = .008$, $\eta_p^2 = .05$. In wave 1 there was a response repetition cost both in the prime offset (RR: 6.73 %; RC: 5.61 %) and probe onset block (RR: 6.47 %; RC: 4.84 %). In wave 2, there was a response repetition cost in the probe onset block (RR: 7.37 %; RC: 5.15 %) but a response change cost in the prime offset block (RR: 5.95 %; RC: 6.73 %). There was no main effect of wave nor did it modulate any other effects (all $F \leq 1.06$; all $p \geq .306$). When analyzing both waves separately, the interaction of response relation and color relation was significant in both wave 1, $F(1, 66) = 28.00$, $p < .001$, $\eta_p^2 = .30$, and wave 2, $F(1, 66) = 23.98$, $p < .001$, $\eta_p^2 = .27$. However, this interaction was not further modulated by valence and/or temporal presentation block in either wave 1 (all $F \leq 0.34$; all $p \geq .564$) or wave 2 (all $F \leq 1.37$; all $p \geq .247$).

General Discussion

In the current study (total *N* = 134), we asked participants to respond to geometric shapes whose color could repeat or switch across prime and probe trial pairs. Between these trials, we presented a positive or negative image either directly after prime offset or directly before probe onset. We observed S-R binding effects in both reaction times and error rates. However, in line with recent high-powered studies by Parmar and Rothermund (2024) and Mocke et al. (2025), affective content did not modulate S-R binding effects in either temporal presentation condition of affective information. Accordingly, we could not replicate the pattern observed by Colzato et al. (2007) in our study, who found enhanced binding effects after presentations of positive images. While changes in the paradigms (e.g., S1R1-S2R2 vs. distractor-response binding paradigm, operationalization of target identity, trial timing) might have some impact on the strength of measured effects, the processes of binding and retrieval and their modulations should theoretically occur in both task types (Frings et al., 2020). Thus, binding and retrieval processes, as examined with the present paradigm, seem to be not influenced by affective information, suggesting that binding and retrieval of action episodes is relatively automatic (see also Giesen et al., 2020; Parmar & Rothermund, 2024).

Yet, affective information had an impact on responding, specifically when presented immediately before probe onset: In line with previous research (e.g., Algom et al., 2004; Augst et al., 2014; Melcher et al., 2011; Öhman et al., 2001), negative images impaired performance. Thus, the affective pictorial content was processed but did not affect binding and/or retrieval. This is in line with, for example, Schöpper, Küpper, and Frings (2023), who found that attentional biases to locations caused by spider stimuli speed up following responses but that retrieval of these locations is not affected by such an attentional bias. Lastly, Colzato et al. (2007) found an impairment for response repetitions after negative content in their shape discrimination task (see also footnote 4), which might reflect a similar effect.

Of note, when we say that S-R binding and retrieval processes are overall unaffected by affective consequences (in line with Mocke et al., 2025; Parmar & Rothermund, 2024), we specifically speak of these processes. A modulating role of valence on action control processes such as binding and retrieval has been found for word stimuli (Giesen & Rothermund, 2011) and when participants are instructed to attend to valence of stimuli (Coll & Grandjean, 2016; Coll et al., 2019; Singh et al., 2018, 2025), when responses become associated with valence (Schöpper, Jerusalem, et al., 2023; Yamaguchi & Chen, 2019; Yamaguchi et al., 2018) or follow a pattern of approach-avoidance (Eder & Hommel, 2013; Eder et al., 2015; Lavender & Hommel, 2007), or when valence is a consequence of an action (e.g., Lavender & Hommel, 2007; Eder et al., 2015). Other processes such as response priming can be affected by reward (e.g., Eder et al., 2020). Rather, we argue that observing a modulation of S-R binding and retrieval by (performance-independent) affective content is unlikely as long as affective content is not presented simultaneously with stimulus and response features (see also Schöpper, Küpper, & Frings, 2023). That being said, we remain agnostic what caused the previous observations of affective modulations of binding and retrieval (Colzato et al., 2007; Waszak & Pholulamdeth, 2009); these might be chance findings due to low overall power and/or the result of highly specific setups (for a discussion, see Parmar & Rothermund, 2024).

Lastly, we chose our images purely based on their valence measure (taken from Dan-Glauser & Scherer, 2011); however, negative images also often come with extreme levels of arousal (e.g. Kuppens et al., 2013) which was the case in our pre-selected images as well. While stimulus arousal of distractors has not been found to modulate S-R binding effects in a sequential distractor-to-distractor repetition paradigm (Giesen & Eder, 2022), arousal of affective images might still have affected performance in the current study. Note, however, that Parmar and Rothermund (2024) also observed a difference in arousal ratings of their affective stimuli with higher ratings for positive compared to negative images but still they did not observe any modulation. Future studies could investigate if arousal has any impact on responding if used as in the current study while de-confounding valence.

Conclusion

Binding and retrieval are two core processes investigated in action control (Beste et al., 2023; Frings et al., 2020, 2024; Hommel, 1998). In line with Parmar and Rothermund (2024) and Mocke et al. (2025) we found no overall modulations of S-R binding and retrieval by affective content – irrespective of temporal presentation. Thus, the processes of binding and retrieval seem to be relatively immune to affective modulations.

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Data availability

Under review, data of the experiments and code for analysis is available at https://drive.google.com/drive/folders/1wfL9Ik9usVVV5nFykTSXZ_dxN9Vyt3fQ?usp=sharing. After acceptance, these will be available at https://www.psycharchives.org/.

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Appendix A1

We analyzed the impact of target repetition and order on reaction times and error rates, resulting in four tests, which we Bonferroni-corrected for multiple comparisons; that is, we will only interpret findings that become significant with $p_{\text{Bonferroni}} < .013$.

Impact of target repetition

As response repetitions with or without target repetitions can potentially lead to different results regarding observed binding effects (Giesen & Rothermund, 2014), we also included trials in which responses repeat without target repetition. This comparison seems also of importance given the different response mapping in Colzato et al. (2007) compared to Parmar and Rothermund (2024) and Mocke et al. (2025): Colzato et al. (2007) used the S1R1-S2R2-paradigm (see also Hommel, 1998) in their study, which allows to de-confound response and target repetitions. In contrast, in Parmar and Rothermund (2024) as in Mocke et al. (2025), response repetitions always came with target repetitions. In fact, the increased error rates for response repetitions in our study might also be attributed to increased difficulty by having two shapes mapped to one response (e.g., a shape change might benefit a response change caused by response repetition heuristics, Pashler & Baylis, 1991, or a bypass rule, Fletcher & Rabbitt, 1978; Krueger & Shapiro, 1981).

We calculated the binding effects separately for trials with response repetitions with, $(\text{RRCC}_{\text{with target}}\text{-RRCR}_{\text{with target}})\text{-(RCCC-RCCR)}$, and without, $(\text{RRCC}_{\text{without target}}\text{-RRCR}_{\text{without target}})\text{-(RCCC-RCCR)}$, target repetitions; for doing this, we always used the same response change trials for calculating the difference values. The calculated binding effects were submitted to a 2 (Valence: Positive vs. Negative) x 2 (Temporal presentation: Prime offset vs. Probe onset) x 2 (Target factor: with target vs. without target) repeated-measures ANOVA. In reaction times, there was a main effect of target factor, $F(1, 133) = 25.28$, $p < .001$, $\eta_p^2 = .16$, with larger binding effects for trials with target repetition (23 ms) compared to without target repetition (13 ms). However, valence and target factor did not interact, $F(1, 133) = 0.55$, $p = .460$, $\eta_p^2 < .01$, nor was this interaction further modulated by temporal presentation, $F(1, 133) = 1.00$, $p = .319$, $\eta_p^2 = .01$. All remaining interactions were not significant (all $F \leq 1.01$; all $p \geq .316$). In the same ANOVA on error rates the interaction of target factor and valence was not significant, $F(1, 133) = 3.45$, $p = .065$, $\eta_p^2 = .03$, and was not further modulated by temporal presentation, $F(1, 133) = 0.74$, $p = .392$, $\eta_p^2 = .01$. There were no other significant effects in error rates (all $F \leq 0.67$; all $p \geq .416$).

To summarize, the affective modulation did not emerge when taking target repetitions into account, suggesting that both binding effects – caused by distractor-response or distractor-target binding (see Giesen & Rothermund, 2014) – are unaffected by affective modulations.

Impact of block order

Previous studies either used conditions that were similar to our prime offset (Mocke et al., 2025; Parmar & Rothermund, 2024) or our probe onset (Colzato et al., 2007) condition, but never both. Thus, we decided to add the order of temporal presentation blocks as a factor to the analysis as it is possible that participants' performance was impacted by the previous temporal presentation block.

We performed a 2 (Valence: Positive vs. Negative) x 2 (Temporal presentation: Prime offset vs. Probe onset) repeated-measures ANOVA with 2 (Order: Prime Offset followed by Probe Onset vs. Probe Onset followed by Prime Offset) as a between-subjects factor on calculated binding effects in reaction times. Order did not interact with valence, $F(1, 132) = 1.51$, $p = .222$, $\eta_p^2 = .01$, or with the interaction of temporal presentation and valence, $F(1, 132) = 2.03$, $p = .157$, $\eta_p^2 = .02$. The remaining effects were not significant with the Bonferroni-adjustment (all $F \leq 4.03$; all $p \geq .047$). In the same ANOVA on error rates, the interaction of order with temporal presentation, $F(1, 132) = 5.30$, $p = .023$, $\eta_p^2 = .04$, with valence, $F(1, 132) = 4.30$, $p = .040$, $\eta_p^2 = .03$, and with the interaction of temporal presentation and valence, $F(1, 132) = 3.90$, $p = .050$, $\eta_p^2 = .03$, did not reach significance under the adjusted α. The remaining effects were not significant with the Bonferroni-adjustment (all $F \leq 5.38$; all $p \geq .022$).

The affective modulation of binding effects did not emerge when taking block order into account. While some interactions were significant at conventional *p*-levels (i.e., $p < .05$), none of these remained significant when controlling for multiple comparisons. To summarize, the explorative analyses suggest no or (if any) weak/unsystematic affective modulations of binding and retrieval, and we are hesitant to deduce if any of these are theoretically meaningful.