The relation between learning and stimulus-response binding

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Abstract

Perception and action rely on integrating or binding different features of stimuli and responses. Such bindings are short-lived, but they can be retrieved for a limited amount of time if any of their features is re-activated. This is particularly true for stimulus-response bindings, allowing for flexible recycling of previous action plans. A relation to learning of stimulus-response associations suggests itself, and previous accounts have proposed binding as an initial step of forging associations in long-term memory. The evidence for this claim is surprisingly mixed, however. Here we propose a framework that explains previous failures to detect meaningful relations of binding and learning by highlighting the joint contribution of three variables: (1) decay, (2) the number of repetitions, and (3) the time elapsing between repetitions. Accounting for the interplay of these variables provides a promising blueprint for innovative experimental designs that bridge the gap between immediate bindings on the one hand and lasting associations in memory on the other hand.

Integrative theoretical frameworks in the domain of human action control use the processes of *binding* and *retrieval* to explain a whole array of findings across different experimental paradigms. This is particularly true for the Theory of Event Coding (TEC; Hommel et al., 2001) and the Binding and Retrieval in Action Control framework (BRAC; Frings et al., 2020), which emphasize the common coding of perception and action.

The assumption of initial binding and later retrieval shares many surface characteristics with two classic building blocks of memory theories, namely *encoding* and *retrieval* (Melton, 1963; Roediger & Abel, 2022). But how do these theoretical approaches actually relate to one another? Even though they might reflect two sides of the same coin, e.g., in terms of binding and retrieval effects showcasing the early stages of a learning process, the actual relation of both fields of research has been surprisingly elusive. Here we propose a way of bridging the gap by appreciating the combined role of decay and the temporal spacing for repeated instances of binding and retrieval.

The problem: how does stimulus-response binding relate to learning and memory?

The human cognitive system represents information in a distributed fashion. When processing a visually presented object, for instance, different features such as the color, shape, and location of that object are processed in separation (Treisman & Gelade, 1980). Constructing an integrated representation of that object requires all relevant features to be combined, i.e., bound together. The same holds true for action plans, which require different components such as the location of a motor goal and the intended effector to be integrated. This integration has been described as formation of, mostly binary, bindings (i.e., links or connections) between the components (Hommel, 2009) and further this concept of bindings resembles the idea of bindings in models of visual working memory (Oberauer & Lin, 2017; Schneegans & Bays, 2017).

Whereas the immediate function of binding is enabling perception and action, the co-activation of different features also comes with robust effects on subsequent perception and action. That is: Re-encountering any feature of a previous binding episode can re-activate, i.e., retrieve, other features that had been bound before (Frings et al., 2020; Hommel et al., 2001). This holds true for features of a stimulus (Kahneman et al., 1992) but, crucially, even for bindings between stimuli and concurrent responses (Frings et al., 2007; Hommel, 1998).

Stimulus-response (S-R) binding and retrieval is particularly interesting, because it offers a parsimonious and elegant explanation for many behavioral phenomena that emerge across a wide range of experimental paradigms. This applies specifically to sequential effects in negative priming, task switching, repetition priming, and other situations in which features relating to concurrent stimulation and features relating to the agent's responses may repeat or switch from one behavioral instance to the next.

Observing carry-over effects from an initial situation to a following situation with similar characteristics is clearly reminiscent of typical experiments on learning and memory. Binding and retrieval effects may be seen as a special case of single-shot learning of a long-term S-R association. Robust learning effects for single pairings of a stimulus and a corresponding response have indeed been documented (Hsu & Waszak, 2012), and it is commonly assumed that learning builds on gradual strengthening of initial associations across repeated iterations of an S-R pairing (Logan, 1988; Logan & Etherton, 1994). In this view, bindings appear to be building blocks that can be used to forge longer-lasting associations, and this theoretical notion has been proposed in several fields of research, such as skill-learning (Poldrack et al., 1999), action-effect learning (Dutzi & Hommel, 2009), and contingency learning (Schmidt et al., 2020). Thus, while S-R bindings can translate into episodic memories (for instance, if a particular stimulus is frequently repeated together with a particular response participants might have a sense of autonoetic consciousness about this particular S-R pairing in the experiment; Tulving, 1972), the most natural and closest relation of S-R bindings is to S-R associations in procedural memory (Squire, 2004).

However, several empirical observations challenge the view of binding and learning being two sides of the same coin, pointing towards separate or at least separable processes (Colzato et al., 2006; Dames et al., 2022; Moeller & Frings, 2017).

An obvious challenge for a hypothesized link between binding and learning is the short-lived nature of S-R bindings. The available database suggests these bindings decay on a timescale of a few seconds (Frings, 2011; Frings et al., 2022; Moeller & Frings, 2017; Pastötter et al., 2021). This time window appears to be too short to enable gradual strengthening of a binding across successive encounters of an S-R pairing. Moreover, a particularly puzzling set of observations relates to a selective impact of, for example, the stimulus configuration on binding and learning (Moeller & Frings, 2017). Correlational analyses further suggest that the strength of different types of bindings is positively correlated across participants such that strong binding and retrieval effects for one type of feature go along with strong binding and retrieval effects for another type of feature (Moeller, Pfister, et al., 2016). No such correlations could be observed between short-term binding effects and longer-term learning, however (Colzato et al., 2006; Herwig & Waszak, 2012).

Here we suggest a solution to the striking disconnect between a simple and plausible theoretical assumption on the one hand and the available evidence on the other hand. This suggestion builds on the conjoint contribution of a binding's decay function, the timing of repetitions, and the number of such repetitions.

A suggestion: decay, number of repetitions, and time between repetitions

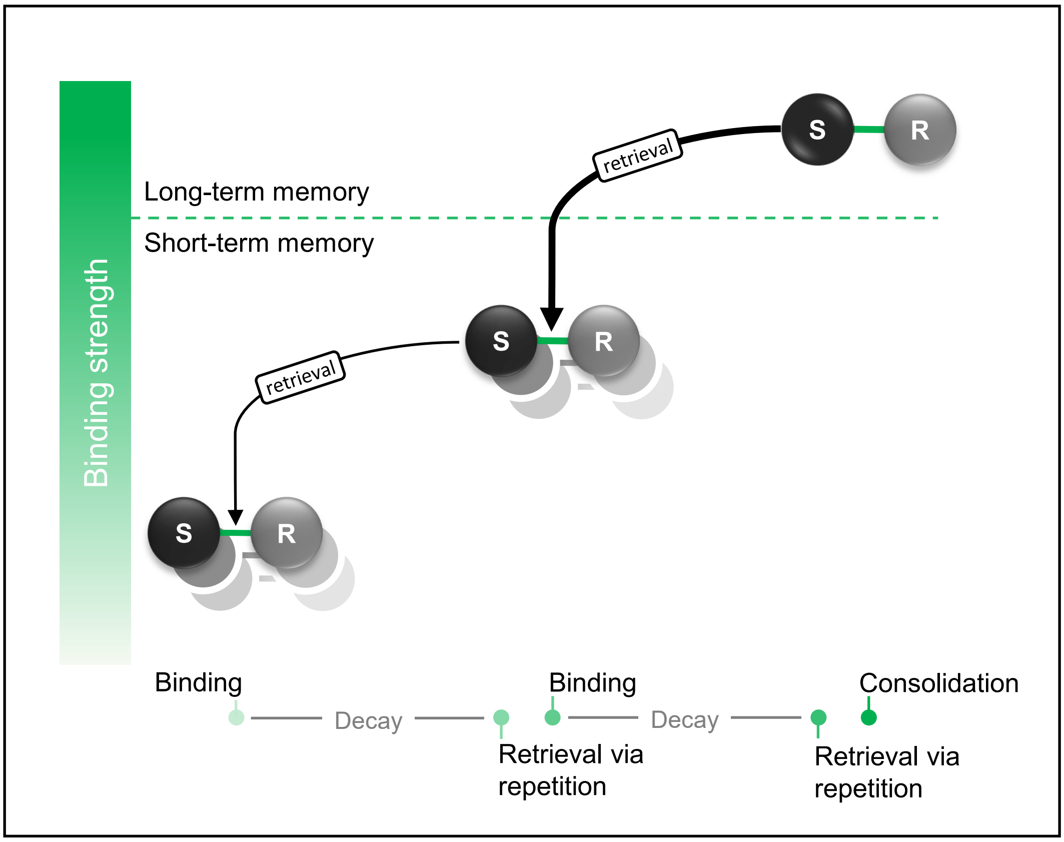
We propose that the relation of (short-term) binding and (long-term) learning can only be properly elucidated when accounting for three aspects that likely affect the durability of S-R bindings: the *decay function* of an S-R binding, the *number of repetitions* of an S-R episode, and the *time between repetitions* of the same S-R episode. These aspects are of course well-known in the literature on learning and memory, where they are discussed as important determinants of consolidation (Melton, 1963; Roediger & Abel, 2022). Yet, strikingly the literature on action control has been blind to these concepts. Here we apply these classical concepts from the literature on learning and memory to the study of binding and retrieval in action control. In doing so, we further highlight that it is the *interplay* of these three variables that provides a promising avenue for bridging the gap between the literatures on binding and on learning/memory. This gap has remained an enigma for over a decade.

Decay, number of repetitions, and the time between repetitions may thus exert a conjoint influence on the consolidation of an S-R episode. **Figure 1** shows a schematic of their proposed interplay. Specifically, when S-R features are bound together, the binding has a particular binding strength, that may partially depend on the activation of its elements (i.e., stimulus and response features). This binding strength is conceptually reminiscent of connection strength in neural network models (Botvinick et al., 2001; Cohen et al., 1992) or association strength in Rescorla-Wagner's model (1972). Once this level exceeds a threshold, the binding will be consolidated into long-term memory. If the initial level of binding strength is lower than the threshold, however, the binding will only be available transiently in short-term memory. In short-term memory, the S-R binding starts to decay after its creation and this decay process eventually drops the binding strength to zero, thus dissolving the binding. Yet, if the stimulus is encountered again, it retrieves the response depending on the current binding strength of the S-R binding. If the retrieved response is appropriate for the current action plan, their binding would be strengthened, increasing the binding strength further. If the response is not appropriate instead, additional binding would not take place for this S-R combination, leaving the binding strength unchanged or even reduced if any of its features enter new bindings with previously unrelated features. The binding strength of the S-R binding therefore depends on its initial binding strength upon its first creation, the time that passes between (partial) repetitions of the S-R episode, and the decay function. For example, let us assume that an S-R binding enters short-term memory with a particular binding strength. After some time has elapsed, the binding strength drops to some extent due to decay. At this point, the same stimulus re-appears requiring the same response. The former binding will be retrieved and its lingering binding strength will be increased – eventually passing the threshold to long-term memory and hence, the binding will be consolidated into long-term memory.

Of course, the proposed idea is not exhaustive in grasping the complexity of memory processes like the transition from short-term to long-term memory and all the debates that have been held there. However, we propose that it incorporates central aspects of (1) how action control short-cuts as offered by binding and retrieval fluctuate in activity over time through decay and the number of repetitions as well as the time elapsed between those repetitions and (2) how these factors contribute to the transition of the S-R trace from short-term to long-term memory.

Figure 1. Suggested factors that determine the transition from short-lived binding to durable associations as encoded in long-term memory.

Note. Initial binding between features of a stimulus (S) and a response (R) come with a certain binding strength, and they are only encoded in long-term memory if this level surpasses a threshold (dashed line). Sub-threshold binding strength will decay (illustrated here in grey-shaded circles) as a function of the initial level of binding strength and the decay rate of the S-R binding. An increase of binding strength is possible if the next pairing of the same stimulus and response occurs sufficiently close in time, while several repetitions may boost the binding strength across the threshold. If the same combination of features is not encountered again in sufficiently close succession, then the S-R binding would decay completely. In a nutshell, a slow decay function of the S-R binding as well as a high number of repetitions and a short time between those repetitions of an S-R pairing should facilitate consolidation even if initial binding strength does not cross the consolidation threshold.



In the following, we present our suggestions for how binding strength of S-R bindings accumulates, discussing the contribution of decay, the number of repetitions, the time that elapses between repetitions, and how these variables interact. In addition, we discuss possible influences for the initial level of binding strength.

Factors that influence the accumulation of binding strength

Decay of bindings has only recently been a subject of research. Hommel and Frings (2020) analyzed S-R bindings for prime-probe sequences of discrete stimuli and associated responses (the so-called S1R1-S2R2 task) and found them to decay within 1 to 5 seconds. Previous research analyzing distractor-based binding and retrieval found that event-files decayed already after 2 seconds (Frings, 2011; Pastötter et al., 2021). Yet, the differences between these studies are very likely due to differences in the entry binding strength because target and distractor bindings were analyzed (target-bindings last longer than distractor-based binding effects; Henson et al., 2014). Yet, the decay function for S-R bindings is all the same irrespective of the stimulus role (as pinpointed in Frings et al., 2022). In contrast, bindings between responses (i.e., R-R bindings) seem to be much more persistent, lasting for at least six seconds (Geißler et al., 2021; Moeller & Frings, 2021). Thus, variants of bindings (like R-R) might have different decay functions but for S-R bindings we can assume the same decay function for target and distractor stimuli. Of course, other factors might also modulate the decay even of S-R bindings. For instance, picture-response bindings might follow a different decay function than word-response bindings just because picture memory is so much better (Standing, 1973). This might explain why Horner and Henson (Horner & Henson, 2009, 2011, 2012) sometimes found target binding effects even after 20 minutes with just one repetition (they used unique picture material as targets) while target-bindings for letters in Hommel and Frings (2020) decayed after 5 seconds.

As argued above, the available data on temporal decay of bindings suggests some variation, especially when considering related phenomena like bindings between responses and effects, responses and responses, or between stimuli (Herwig & Waszak, 2012; Hommel & Colzato, 2004; Hommel & Frings, 2020; Moeller & Frings, 2021; Moeller, Pfister, et al., 2016; Whitehead et al., 2020). Moreover, many experimental paradigms used to study binding and retrieval in action control may have elicited particularly fast decay. This is because such paradigms often vary stimuli and responses orthogonally without contingency between both to avoid learning effects. In such designs, retrieving an S-R binding upon re-encountering a stimulus is helpful in only 50% of the cases, i.e., when it contains the currently appropriate response. It is harmful to performance in the remaining 50% of the cases, however, because the retrieved response conflicts with the to-be-executed response. Research on learning has suggested that the human cognitive system is highly sensitive to the information conveyed by a single behavioral episode (Behrens et al., 2007). A single episode is informative only if it represents the current structure of the environment, e.g., when certain stimuli contingently call for certain responses. Maintaining a binding or association between a stimulus and a response is not useful, however, if S-R pairings vary unpredictably, as in common experimental protocols to study binding and retrieval. This is even true for attempts to investigate the relation between S-R binding processes and learning (Herwig & Waszak, 2012; Moeller & Frings, 2017). Conversely, bindings were observed to last longer when introducing contingencies in binding and retrieval instances, i.e., if the same seemingly irrelevant stimuli and responses were coupled repeatedly (Frings et al., 2015).

The second factor contributing to the accumulation of binding strength is the *number of repetitions* of an S-R binding. In typical action control tasks, responses and stimuli are varied orthogonally. In addition, the manipulation of sequential conditions and analyses in these tasks tackle transitions between successive trials (n-1 to n) or between prime and probe within the same trial. Thus, S-R repetitions are typically only considered between these immediately following action episodes and in turn the number of exact, experimenter-controlled repetitions is N = 1 without any intervening trials. Yet, there are exceptions in studies that tackled the relation between binding and learning. Frings and colleagues (2015) repeated the exact same (picture) distractor with the same response five times (with intervening trials) before testing for distractor-based retrieval. In this setting, distractor-based binding effects still emerged after two minutes. In several studies, the authors introduced contingencies between colors and words in a task that required participants to respond to print colors of words (Arunkumar et al., 2022; Giesen & Rothermund, 2015; Giesen et al., 2019; Schmidt et al., 2020). While performance was generally better for frequent color-word combinations than for infrequent ones, this contingency effect typically disappeared in analyses that controlled for S-R binding effects (differences between repetition and switch of the response compared to the last occurrence of a stimulus) and the distance of the last occurrence of the stimulus. This can be interpreted as an indication that S-R binding processes play a role in contingency learning (Schmidt et al., 2016).

Another aspect that follows from the orthogonal variation of stimuli and responses in most S-R binding tasks is that oftentimes the stimulus will be repeated without the particular response. Thus, the stimulus will retrieve an S-R binding that is incompatible with the currently demanded response. It seems safe to say that such repetitions will not strengthen the incompatible S-R link. Instead, the incompatible S-R link might be weakened. This speculation bears close resemblance to a phenomenon in memory research, namely retrieval induced forgetting (RIF; Anderson et al., 1994). In RIF studies, practising only half of formerly learned word-pairings diminishes memory for not-practiced but also formerly learned word-pairings;

relevant for our purpose here is that RIF has not only been shown with complex verbal utterances but has also been demonstrated with arbitrary motor patterns such as sequences of keypresses (Tempel & Frings, 2013, 2015) and has been related to motor inhibition (Tempel et al., 2020). Thus, encountering a particular stimulus that is already bound to a particular response will retrieve the S-R binding but if this link is incompatible it might be dissolved. Alternatively, the orthogonal combination of stimuli and responses might leave their bindings at a similar binding strength. So concurrent retrieval of similarly strong bindings would lead to interference, hampering consolidation. However, whereas some studies indeed suggest larger (Schmalbrock et al., 2022) or longer lasting (Dobbins et al., 2004; Horner & Henson, 2012; Moutsopoulou et al., 2019; Whitehead et al., 2020) binding effects with unique stimulus materials (albeit not unique responses), other findings indicate that short lived action control effects are not due to interference but rather due to decay (Hommel & Frings, 2020).

In episodic memory research, it is a prominent idea that memories are bound together by a context representation that changes slowly over time (Howard & Kahana, 2002). Although we think that S-R bindings most closely match traces in procedural memory, empirical evidence still suggests that as the number of repetitions of S-R episodes increases, S-R bindings are integrated and retrieved in an increasing number of slightly variable contexts. Qiu et al. (2022) demonstrated that context variability is indeed a modulating factor for S-R bindings and that contexts are even bound to responses directly if trial-to-trial context variability is (relatively) high, but not if it is low. In the latter case, with an increasing number of repetitions of a particular S-R binding, multiple contexts can prompt retrieval of the S-R binding. This increases the binding strength of the S-R binding and pushes it toward consolidation into long-term memory. Following this line of reasoning, memory consolidation, i.e., the transfer of S-R bindings from short-term memory to instances in long-term memory, occurs through the process of de-contextualizing S-R episodes during repeated encounters in different situations (Yonelinas et al., 2019).

The third factor to influence the accumulation of binding strength is the *time that elapses between repetitions*. Yet, there are no systematic attempts – to the best of our knowledge – to disentangle the impact of repetitions and the time that elapses between these repetitions in S-R binding tasks. A particular S-R binding might be repeated in an experiment but if the time between the creation of the binding and the repetition of the same episode is so long that the binding has already decayed, according to our approach, the repetition will not accumulate binding strength.

The only thing that has been systematically analyzed is the time that elapsed between trial n-1 (where an initial S-R binding is build) and trial n (where retrieval of the S-R binding is triggered in case of stimulus repetitions) in typical sequential tasks. Here it has become clear that distractor-based bindings typically dissolve after 2 seconds (e.g., Frings, 2011; Moeller, Frings, & Pfister, 2016), target-based bindings after 5 seconds (e.g., Hommel & Frings, 2020) while other variants like R-R bindings persist easily for 5 seconds (Moeller & Frings, 2021). According to our idea, the shorter the time between repetitions the more binding strength accumulates for an S-R binding. Yet, it is noteworthy that learning and memory research instead suggests that items can actually profit from spaced activation. It is a well-established finding that learning is more effective when studying or practicing is spaced out over time, rather than when cramming or massing practice (Delaney et al., 2010; Roediger & Abel, 2022). Contextual variability is one factor that has been suggested to contribute to this spacing effect in episodic memory. According to this suggestion, due to changes in contexts over time, spacing creates multiple context associations with item representations that can be used for memory retrieval. In addition, there are studies that suggest that spacing can also enhance the learning and retention of motor skills, which are closely related to procedural memory (Smith & Scarf, 2017). In the literature on conditioning, learning profits from massed repetitions in the beginning but then after the association between conditioned stimulus and the unconditioned response has been established, conditioning profits from spaced repetitions (Rescorla & Wagner, 1972; Sutton & Barto, 1998). Transferred to S-R bindings, increased time between S-R repetitions should thus promote the binding strength of S-R bindings within short-term memory and their consolidation into long-term memory. However, this assumption can only hold true as long as an S-R binding never completely decays before the next repetition. Best consolidation might therefore rely on spacing that is close enough for incomplete decay, but also long enough for sufficient separability of individual response episodes. In cases of particularly short decay periods (like in distractor-response binding), decay might be almost complete at a time allowing for separability. In turn, a larger number of repetitions might be necessary for long-term consolidation. Yet, with overly close spacing in this specific case, consolidation might be prevented by insufficient separability (see Moeller & Frings, 2017).

Factors that influence the entry binding strength

A crucial aspect of our idea as depicted in **Figure 1** is the entry binding strength. If, for instance, the entry binding strength is so high that the S-R binding directly enters long-term memory our musings about the interplay of decay, number of repetitions, and time between repetitions become obsolete. Yet, in most cases immediate supra-threshold binding strength would probably not be the case – then, the entry binding strength would influence how many repetitions are necessary or how much time between repetitions can pass to accumulate binding strength before the S-R binding dissolves. Generally speaking, the entry binding strength of an S-R binding might be compared to similar concepts in the learning and memory literature like, to name just one example, to the association strength in classical models of conditioning (1972). Yet, we here only shortly discuss factors that impact upon the entry binding strength of S-R bindings from the action control literature.

Previous research already suggested that the 'role' of the stimulus to which the response is bound or which starts the retrieval process is important (Henson et al., 2014). Target-binding effects are much larger and longer lasting as compared to distractor-based binding effects albeit the decay function may be the same (Frings et al., 2022). Accordingly, the entry binding strength must be higher. The underlying mechanism seems to be attention or task relevance (Moeller et al., 2019). That is, the distribution of attention at the time of S-R binding seems to influence the entry binding strength of the attended items (Moeller & Frings, 2014). Yet, attention towards a stimulus is not only allocated due to its role in the task, but might in fact be allocated due to many other factors like salience (in the context of S-R bindings, Schmalbrock et al., 2021) or reward (in the context of S-R bindings, Waszak & Pholulamdeth, 2009).

Open questions

Several intriguing questions emerge from the present framework: Does re-activating a previous binding provide an additive increase to the binding strength, or does the increase depend on the current binding strength? Do decay functions differ across binding strengths? Can multiple independent S-R bindings accumulate in parallel? If so: Do they interfere with each other? How do partial rather than full repetitions of an S-R episode affect the accumulation of binding strength?

The problem space opened up by the present framework, therefore, cannot be tackled by a single experiment. Assessing the interplay of its three major variables requires complementary empirical efforts instead. The present framework should thus be seen as a blueprint for innovative experimental designs that study the joint contribution of decay, number of repetitions and temporal spacing of these repetitions.

Concluding remarks

Binding and retrieval of S-R features are key processes in human action control. The relation to learning is almost imposing. Is it really plausible then to assume that these fundamental processes of action control are completely detached from learning? No, but the available evidence seems to suggest so. We here emphasized three variables: The decay function of S-R bindings, the number of repetitions, and the time that elapses between those repetitions to theoretically link S-R binding and learning. Considering these variables and in particular their interplay provides a promising explanation why previous studies on S-R bindings typically failed to find evidence for learning. Against the background of our approach, the link between (short-term) S-R bindings in action control research and the (long-term) learning literature thus appears to be within reach.

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