Trends in Cognitive Sciences

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Opinion

Binding and Retrieval in Action Control (BRAC)

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Human action control relies on representations that integrate perception and action, but the relevant research is scattered over various experimental paradigms and the theorizing is overly paradigm-specific. To overcome this obstacle we propose BRAC (binding and retrieval in action control), an overarching, integrative framework that accounts for a wide range of seemingly unrelated findings by assuming 'two core processes: feature binding and retrieval'. In contrast to previous approaches, we define binding and retrieval as functionally different and separable processes that independently contribute to the observed effects. Furthermore, both processes are independently modulated by top-down and/or bottom-up processes. BRAC organizes the literature on action control in novel ways, and relates diverse independently investigated action-related phenomena from different research fields to each other.

Highlights

We introduce the BRAC framework. The framework is tailored to the sequential structure of action-control tasks and thus can integrate the vast paradigm-specific literature on action control.

BRAC is based on two core processes: feature binding and retrieval. We present evidence that these processes operate independently of each other and are separately modulated by top-down and bottom-up influences.

BRAC emphasizes the need to disentangle the processing level from the level of observation. Previously published results in action control should be re-evaluated against the framework because previous research did not separately modulate the two core processes.

BRAC provides a framework for discussing action-related phenomena beyond the research area of action control, including attention, memory and learning, and motivation.

A Cognitive Approach to Action

Human cognition serves adaptive action. Through their actions humans shape and influence their physical and social environment [1]. They acquire their ability to turn movements (arbitrary, nongoal-directed activities [2]) into goal-directed actions by integrating movements with their perceptual effects, and this in turn allows them to 'act on purpose' – to anticipate wanted (perceptual) effects so as to select and initiate actions that produce these effects [3,4]. Put differently, by connecting specific behaviors with specific outcomes, humans learn to act intentionally [5].

The idea that action and perception are closely intertwined was already suggested by **ideomotor theory** (see Glossary) ([6]; more recent approaches are presented in [7–10]; overviewed in [11]), as well as by Piaget's [12] approach to cognitive development. This idea continues in current approaches to action control (Box 1) that focus on the integration of perception, action, and outcomes – and is applicable, as we will argue, to various well-established experimental tasks that are commonly used to study action control. These tasks have one important procedural characteristic in common, namely that they all rely on a sequential prime–probe structure – meaning that processing of information at one occasion (a prime trial) influences processing and responding at a subsequent occasion (a probe trial). However, each action-control task has been developed to measure a specific aspect of action, and the specific results of these action-control tasks have been interpreted by paradigm-specific accounts.

We propose an overarching perspective that (i) is tailored to the prime–probe structure of action-control paradigms, (ii) allows integration of results that were gathered with these paradigms, and (iii) can replace paradigm-specific mechanistic explanations with a unifying explanation that covers all these paradigms, and that can be related to research on action in general. The framework we propose comprises two core processes: feature binding and retrieval (Figure 1).

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Box 1. Action-Related Models of Episodic Binding and Retrieval

Instance Theory

The basic idea was that a stimulus and its response instruction are integrated into an episodic representation (an instance). When the stimulus repeats, previous instances are automatically retrieved including response instructions (e.g., in case of a distractor the retrieved response instruction would be 'ignore this stimulus'). Thereby, actions are modulated by previous instances of the stimuli (e.g., Neill [94] used this theory to explain negative priming because the probe target is the previous prime distractor and hence retrieves the instruction 'ignore this stimulus').

Parallel Episodic Processing (PEP) Model

The PEP model is a neural network model in the tradition of exemplar memory models [18,95–97]. Each encounter with a stimulus is saved together with the particular response in a memory trace. In addition, all traces have a decay function. If a stimulus is re-encountered, all previous traces are retrieved and these impact upon behavior in proportion to the strength of their traces. Several retrieval-based phenomena (including some action-control tasks) have been modeled with this approach [42].

S–R Binding Approaches to Memory

Henson and colleagues [98] have argued that S–R binding and retrieval can substitute component processes in processing models of memory [99]. By retrieving a previous response produced by stimulus repetition the typical and more controlled component process route (such as identifying the stimulus, generating the motor program, and then executing it) might be skipped and a response is directly retrieved instead of generated. EEG [100] and fMRI [101] data suggested that even a single encounter with a stimulus leads to an S–R memory trace that might be sufficient to bypass response generation during the next encounter.

Theory of Event Coding (TEC)

The basic idea of TEC is that perceived and produced events (stimuli and responses) are cognitively represented in so-called event-files (i.e., episodic representations) and that these representations interact to generate perception and action. The TEC is a very general framework that explains the modulation of action as a result of retrieval of previous event-files. In addition, the planning and selection of action in light of anticipated action-effects trigger the motor programs that were formerly integrated with the effects [14].

The BRAC Framework

Our major claim is that many aspects of cognition such as perception, attention, memory, and motor planning are best understood by their contribution to action control. Accordingly, many observations that have been made in areas investigating these functions can be accounted for by core processes that are known to drive action control.

Building on existing action-control approaches, we assume that features of the stimulus environment (S; stimulus, context, cue), a response in that environment (R; decision, effector), and its subsequent effects (E; perceptual and affective) are integrated (or bound together) into an **event-file** [13]. Repetition of any S, R, or E feature triggers the retrieval of previous event-files comprising codes of the same features, and these can impact on current performance. If, for instance, a participant responds to a stimulus S with a keypress (the R component), which then triggers a particular perceptual effect (a change or disappearance of the stimulus), the whole episode consisting of the S features (the color, shape, location, and also the meaning of the situation), the R features (the particular effector, its location, the key, but also the semantic representation of the response meaning), and the E features (tactile or visual feedback, and also evaluative outcomes) are bound together into an event-file. Re-encountering one of the features then leads to automatic retrieval of all the elements of the previous episode (S, R, and E). Whether such retrieval results in performance costs or benefits depends, however, on the particular circumstances.

BRAC adopts the assumption of the theory of event coding [14] that stimuli, responses, and action effects are coded in a common representational format that allows us to treat features of S, R, and E interchangeably: event-file retrieval can be triggered by any type of feature. Thus, even a

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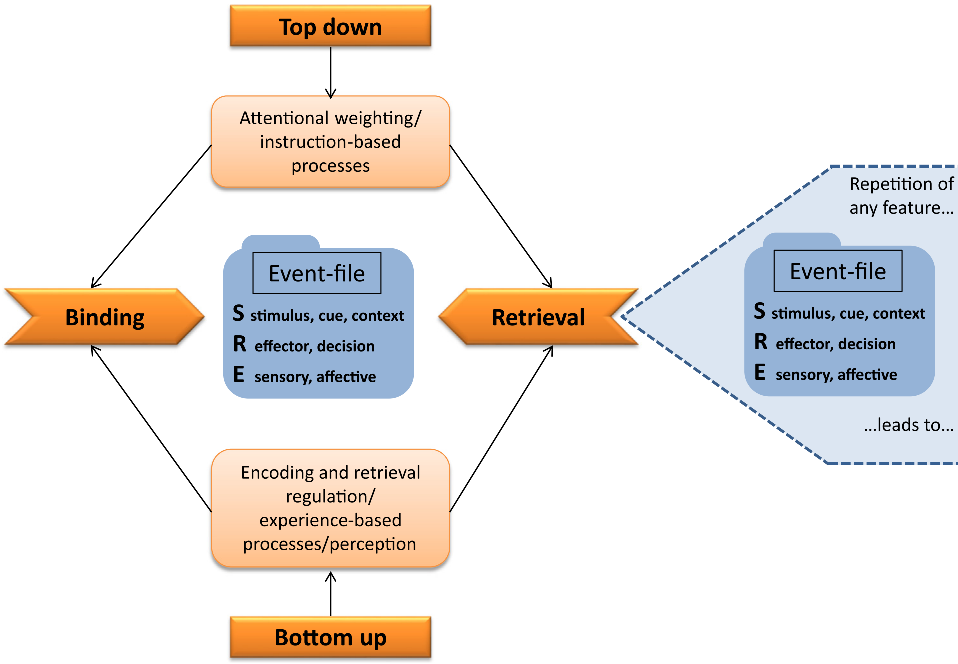

Figure 1. The BRAC (Binding and Retrieval in Action Control) Framework. This framework postulates two core processes: (i) feature binding of stimulus (S), response (R), and effect (E) features into an event-file; then, upon repetition of any feature, (ii) an automatic episodic retrieval process that retrieves the previous event-file including all features. Feature binding and retrieval operate in separation and are independently modulated by top-down and bottom-up influences.

repeated response retrieves the previous S and E features [15], and a stimulus that is expected to induce response conflict might induce a perceptual conflict upon feature retrieval, as measured by early lateralized visual electroencephalography (EEG) [16]. We recently showed that even anticipated responses retrieve previously integrated sensory features [17] – confirming that R features and S features can initiate retrieval equally well.

The BRAC framework emphasizes that the immediate past shapes current behavior. By stressing this point, BRAC builds bridges between various action-control tasks that almost always rely on a sequential prime–probe design. Responses in the prime (or trial $n - 1$) affect responding in the probe (or trial n). The sequential design of action-control paradigms has several important theoretical consequences. For instance, because of their sequential character, it is always possible that episodic retrieval processes in the probe retrieve information from the prime [18,19]. As a consequence, effects that are observed in these tasks are in principle open to different explanations (in terms of retrieval, inhibition, reconfiguration, partial match, etc.). This inherent complexity of the sequential paradigms employed to study intentional action in laboratory settings probably resembles the complexity of intentional actions themselves in real-world settings [20]. We see this complexity as a strength because this is a prerequisite to arrive at a realistic picture of the various determinants of action control and of their interactions. Nevertheless, making adequate use of these paradigms to investigate action control requires a conceptual framework that (i) allows integration of findings across different paradigms, and (ii) stresses the separation of processes taking place at the prime from processes taking place at the probe. The separation of feature binding in the prime, and retrieval at the probe, is a core assumption of the BRAC framework.

Glossary

Action-planning tasks: the key question in action-planning studies concerns how the mental preparation of an action in a prime trial impacts on the initiation of the prepared (or a related) action in a probe trial. Feature binding during action planning can hinder or facilitate the initiation of feature-overlapping actions, although the specific conditions and reasons for such costs and benefits have remained elusive so far.

Distractor–response binding task: an action-control task in which a distractor is repeated (as distractor) or changed between two consecutive displays while the response also repeats or changes. Distractor repetition effects are modulated by the response relation between prime and probe.

Event-file: an internal feature-based representation of stimulus, response, and effect features. The concept of an event-file follows the tradition of Kahneman and Treisman's [93] object files (that consisted only of stimulus features).

Gratton effect: denotes the sequential modulation of congruence effects and more specifically how conflicting information is handled by cognitive control. Ignoring incongruent information in trial n seems to be easier if trial $n - 1$ was also incongruent (i.e., congruency effects are typically smaller after an incongruent compared with a congruent trial).

Ideomotor theory: the basic assumption of this >100 year old approach is that for an action one must first anticipate the perceptual effect the action will produce (this is labeled the 'idea'). The motor program that will lead to this anticipated perceptual effect is then retrieved and executed.

Negative priming task: an action-control task that was designed to investigate the processing of distracting stimuli while selectively responding to a target. In this task, on each display a target and a distractor are presented. Repeating the prime distractor in trial $n - 1$ as the probe target in trial n leads to performance costs.

Repetition priming tasks: a family of tasks where a stimulus repeats between consecutive displays while the response also repeats or changes. Repetition priming effects emerge at the perceptual level when the same stimulus appears a second time, and they emerge also at

Integration of Task-Specific Explanations in Action Control

An important benefit of the framework is its potential to reinterpret empirical phenomena of action control across a wide range of experimental paradigms while retaining the level of detail of theorizing that has been achieved in these paradigms. BRAC can account for well-known effects observed in action-control tasks such as **task-switching tasks** [21], **negative priming tasks** [20,22], **repetition priming tasks** [23], **S1R1–S2R2 tasks** or **distractor–response binding tasks** [24–26], **action-planning tasks** [27–29], and tasks measuring sequential modulation of interference (i.e., the **Gratton effect** [30]), thereby stressing the convergent nature, if not identity, of the underlying processes. All these different paradigms have been designed to study specific aspects of action control. For example, ignoring distractors is assessed in the negative priming paradigm, flexibility and rigidity of action control in multitask environments is measured in task-switching, and adaptive changes in action modes (e.g., speed vs accuracy) are assessed via the sequential modulation of interference. Sophisticated theoretical models have been developed for each of the effects that these paradigms have produced. Importantly, however, for each of these paradigm-specific explanations, alternative explanations in terms of binding and retrieval can be suggested (Table 1 summarizes the procedural details of the tasks, the elicited effects, the typical explanation, and how BRAC can describe the effects in terms of binding and retrieval).

For instance, task-switching costs emerge as a sequential effect if the task changes rather than repeats from prime to probe. It has been argued that task-set inhibition after the prime leads to task-switching costs [31] because the incompatible task-set in the prime is inhibited and must be reactivated in the probe. Nevertheless, task-switching costs can be explained under the BRAC framework as task-induced retrieval of incompatible S–R mappings. Because the stimulus categories repeat from prime to probe (even in task-switch conditions), repeating the task context in the probe retrieves the prime event-file that includes the S–R mapping of the prime task, which in task-switch sequences interferes with current task demands of the probe [32–36]. The same approach can be taken to explain negative priming [20]. In this task, participants respond to a target while ignoring a distractor on each prime and probe display. The original and still accepted interpretation invokes inhibition (or episodic retrieval of do-not-respond tags attached to the prime distractor [37]). A distractor-to-target repetition that typically leads to performance costs (i.e., the negative priming effect) was interpreted as reflecting lingering prime inhibition or reactivated do-not-respond tags [38]. BRAC assumes that all prime stimuli and the response are integrated into a prime event-file that is retrieved when the prime distractor repeats as the probe target [22,26] – the prime response is always incompatible with the probe response, and hence performance costs emerge. There is clear evidence that the prime response is indeed retrieved (and not a general inhibition or instruction to not respond) because errors in the probe indicating prime response retrieval are much more likely than are random errors [22,39].

For many other action-control effects, task-specific explanations can also be replaced by explanations in terms of binding and retrieval (Box 2 for further in-depth discussion of the BRAC approach to other action-control tasks). By unifying and integrating these explanations in terms of binding and retrieval, BRAC has the potential to make a strong contribution to theoretical parsimony and consistency. For instance, with respect to the two action-control paradigms discussed above, it might be possible to link the decade-long debate on inhibition versus retrieval in the negative priming paradigm [20,26] to the debate on inhibition versus retrieval in task-switching [31,40,41].

There have been first attempts to relate the different action-control phenomena directly to each other. It was shown that episodic retrieval processes that mediate effects in different action-control tasks can be modeled by a single cognitive architecture [42]. We also showed that effects

the response level when the response repeats.

S1R1–S2R2 task: an arbitrary response (R1) is executed together with a stimulus (S1). On the next display a further stimulus (S2) is presented to which the participant must respond (R2). If stimulus and/or response features are repeated between S1R1 and S2R2, facilitation (in the case of complete repetitions) or interference (in the case of partial matches) is observed.

Task-switching task: an action-control task to study cognitive control/flexibility in dynamic and changing environments with different action demands. Task-switching costs emerge as a sequential effect if the task changes instead of repeating from trial $n - 1$ to trial n.

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Table 1. Overview of Action-Control Paradigms and How BRAC Can Explain the Effects in Terms of Binding and Retrieval

Experimental paradigm	Typical procedure	Behavioral effect	Established explanation	BRAC explanation
Task-switching paradigm [13]	Prime–probe sequences in which one of two tasks (e.g., task A, odd/even judgment; and task B, vocal/consonant judgment) are presented on each display, typically using the same response keys for both tasks	Switching costs: task changes from prime to probe lead to worse performance than task repetitions	Task set inertia: persisting activation of previous task set interferes with a task-switch, as well as persisting inhibition of the competitor task in the previous trial, slows down switching to this still inhibited task	Stimuli and task sets are integrated in the prime and, upon category repetition in the probe, the previous event-file is retrieved, including the incompatible task set, leading to interference
Negative priming paradigm [14,15]	Prime–probe sequences consisting of a target and a to-be-ignored distractor in the prime and probe displays	Negative priming effect: distractor-to-target-repetitions lead to performance costs	Distractor inhibition and/or episodic retrieval of a do-not-respond tag: ignoring a prime distractor leads to inhibition of that stimulus or the attachment of a do-not-respond tag. In case of repetition as a probe target, this leads to performance costs	Prime stimuli and response are integrated, and this event-file is retrieved if the distractor repeats, thereby retrieving the incompatible prime response during the probe, causing interference
Tasks with sequential modulation of interference [17]	Prime–probe sequences in tasks with targets and distractors that are congruent or incongruent with the target (AAA vs ABA); congruency in the prime is independently varied from probe congruency	Gratton effect: probe congruency effects (difference between incongruent and congruent conditions) are smaller after incongruent primes	Cognitive control is enhanced after incongruent prime trials (in response to the conflict during the prime), leading to smaller congruency effects in probes after incongruent primes	Incongruent trials (ABA) after incongruent trials (ABA) retrieve the previously integrated prime response that is compatible with the probe, resulting in smaller congruency effects
Repetition priming paradigm [16]	Prime displays (with one stimulus) are followed by probe displays with one stimulus that is either repeated or not	Repetition priming effect: participants respond faster to repeated stimuli	Spreading activation at perceptual and response levels	Prime stimuli are integrated with a response (executed or not), and upon repetition retrieve the prime response which facilitates the probe response
Action-planning paradigm [20]	Prime–probe structure but the prime response is only mentally planned	Action-planning costs: probe response times increase when some action features change from prime to probe response	Modification of the original action plan which takes more time depending on how much modification is necessary	Features of the planned action are integrated and involuntarily retrieved by features of the probe response
Binding tasks: S1R1–S2R2 or distractor–response binding paradigm [21–23]	Prime–probe sequences in which target or distractor repetitions are orthogonally varied to response repetitions	Binding effects: interaction of stimulus × response repetitions	See BRAC explanation	Prime stimuli and response are integrated and this event-file is retrieved if a stimulus repeats, thereby facilitating or hindering responding (depending on response compatibility)

from different ‘binding tasks’ correlate highly in young, healthy subjects [43], suggesting common underlying processes. In another study, we [32] combined binding approaches from task-switching and negative priming. These observations support our claim that many (often theoretically not overly parsimonious) task-specific explanations can be unified in terms of binding and retrieval as represented by BRAC.

Binding and Retrieval as Separate Processes

Action-control effects are commonly investigated in sequential prime–probe paradigms that imply both the integration of features and the retrieval of the resulting event-file. Accordingly, almost all resulting experimental observations presuppose both integration and retrieval, and typically these two processes and their relative contributions to action-control effects are not separately

Box 2. The BRAC Approach to Further Action-Control Paradigms

Action-Planning Tasks

These tasks use a prime–probe structure but typically the prime response is mentally planned, instead of being carried out, before probe onset. In fact, the reported results in the literature are somewhat inconsistent with respect to whether feature repetitions between prime and probe lead to facilitation or interference [102]. Explanations in terms of code occupation (features of the planned response are bound and less accessible for the prime response) can be extended under the BRAC framework by assuming that during probe processing the prime event-file is retrieved, thus causing interference if the prime response (even if not yet executed) is incompatible with the probe. There are already attempts to explain these kinds of effects in terms of binding and retrieval [103,104].

Sequential Modulations of Interference in Selection Tasks (Yielding the Gratton Effect)

The Gratton effect is commonly attributed to the increase of control processes, even though the design of the respective sequential tasks is in principle open to an account in terms of the retrieval of stimulus–response bindings. Importantly, because the effect is particularly strong for stimulus repetition sequences, this opened the door for an alternative explanation in terms of binding and retrieval (e.g., [105,106]) by assuming that feature repetition leads to retrieval of the previous event-file including the compatibility of the previous episode. Nevertheless, the BRAC framework might also explain Gratton effects without stimulus repetitions because the task or context might be integrated into an event-file and upon repetition might retrieve the previous control state [30].

Repetition Priming Tasks

The BRAC framework assumes that the probe target retrieves the prime event-file, including the response in the repetition priming paradigm that is compatible with the probe response – leading to facilitation (i.e., repetition priming effects). BRAC can be used to explain repetition priming effects at the perceptual level as well as at the response level (where the main locus of this effect is typically assumed [107]) because stimulus and response features are coded in event-files. In the typical repetition priming task, several intervening trials might be presented between prime and probe – but the literature on S–R binding and retrieval fits with this because binding effects also survive intervening events [38,108–110].

assessed [44]. Accordingly, we recommend reserving the term 'binding' to the process of feature integration proper – and that this binding process is not confused with the retrieval process that is necessary to demonstrate that the features have been bound. We also suspect that, for most known modulating variables of action-control effects, it remains so far unclear whether they impact upon feature binding, retrieval, or both.

In many situations it is theoretically interesting and experimentally feasible to modulate binding and retrieval in distinct ways. For example, it has been reported [45] that perceptual grouping of distractors and targets affects distractor-based binding effects. Distractors that are grouped together with the target produce larger binding effects – yet grouping was manipulated in prime and probe displays. We recently reported [46] that color-grouping of distractors and targets in the prime display leads to enhanced feature integration and in turn to larger binding effects, whereas color-grouping of distractors and targets leads to smaller binding effects when applied in the probe display – suggesting that grouping has opposite effects on feature integration and retrieval.

In the same vein, spatial attention towards a distractor in the prime display and in the probe display was separately modulated [47]. Although cued spatial attention had no effect on integration in the prime, it boosted retrieval in the probe [48]. It has been shown that drawing attention to particular feature dimensions affected the strength with which repetition-induced retrieval of features from this dimension interfered with ongoing processing; however, this effect was independent of whether the attentional cue was given before or after the integrated stimulus–response episode, suggesting that only retrieval was affected [44]. In concert, these findings suggest that binding and retrieval should be experimentally disentangled and their separate contributions to observed effects should be stressed. Our recent results therefore highlight the necessity to re-evaluate previous findings from paradigms using prime–probe sequential designs against the suggestion of the BRAC framework to disentangle feature binding and retrieval.

Top-Down versus Bottom-Up Influences on Binding and Retrieval

Conceptual problems of the coarse-grained separation of cognitive processes into top-down versus bottom-up [49] notwithstanding, our current version of BRAC distinguishes between effects that originate in the observer (e.g., the impact of the experimental task instruction, perceived relations between the stimuli) and effects that reflect the impact of the current sensorimotor experience. Our framework postulates that such top-down and bottom-up factors independently impact on feature binding and retrieval (binding and retrieval are thus not understood as top-down or bottom-up *per se*). That is, we assume that top-down control, such as different levels of action representation [50], attentional weighting of stimulus features [51], and metacontrol of action–perception links [52], impacts on the processes of feature binding and retrieval independently, and perhaps in different ways (by operating on different levels of representation such as task rules, framing, mind sets, speed/accuracy tradeoffs, and instruction-based effects). Control processes can thus influence the binding process (features receiving much attention might be more likely to become integrated into event-files [24]), the retrieval process (features that are ignored might be less effective retrieval cues [47]), or both. Relatedly, it has been shown that binding processes between stimuli and responses are influenced by the task instructions: S–R binding effects emerged when the task rules stressed specific stimulus–response assignments, whereas instructing participants to categorize the same stimuli on the basis of superordinate semantic features eliminated these effects [53].

There is evidence that can be interpreted as 'bottom-up control' of binding and retrieval; that is, the sensitivity of integration and/or retrieval to stimulus contingencies [54], affective states [55–57], and perceptual configurations (as a result of Gestalt mechanisms [45,58]) might indicate control of binding and retrieval processes by variables not originating in the observer. In addition, location repetitions versus changes of stimuli to which one responds actually influence whether features and responses are bound in a more binary fashion (when location changes) or whether the stimulus features are integrated into a single object and this feature compound is bound to the response [59]. Thus, in BRAC both top-down control and bottom-up control are assumed to exert their independent influences on binding and retrieval.

New Hypotheses and Questions Generated by the BRAC Framework

Focusing on the commonalities between seemingly different experimental paradigms or research fields provides an opportunity to turn the typical analytic approach to human cognition into a synthetic approach [18,42,60] which starts with a transparent, well-understood set of core mechanisms that are combined to explain as many aspects of as many different experimental effects as possible. We consider it likely that BRAC will not address all possible aspects of the mentioned observations, whereas it might reorient the theoretical interest to overarching cognitive mechanisms rather than to processes specific to arbitrary individual paradigms.

The strong hypothesis-generating potential of BRAC derives from two implications. First, the systematic distinction between feature integration and feature retrieval raises many questions regarding the interpretations of previous findings. In most cases, what is currently is attributed to modulation of binding may well turn out to reflect modulations of retrieval. Hence, systematic research will be necessary to experimentally disentangle the contributions of binding and retrieval processes to previous results in the vast literature on action control.

Second, the emphasis of BRAC on the commonalities between different paradigms allows numerous new hypotheses. Given that these commonalities refer to overlap of mechanisms rather than to overlap in paradigmatic details, it will be possible to generalize to entirely different paradigms what hitherto was considered to represent paradigm-specific effects of experimental manipulation. For instance, it should be possible to generalize to all action-control paradigms the observation that attentional and perceptual parameters targeting the stimulus and response components of event-files (salience, grouping, feature weighting, inhibition [58,61]) affect event-file binding and/or retrieval. The same holds for contextual influences [62] and the impact of emotion [55]. BRAC suggests expanding research beyond the almost exclusive paradigm-specific approaches to action control, and instead advocates describing the underlying processes by a single overarching framework. Accordingly, many paradigm-specific results should be replicated in action-control paradigms that differ from those in which the results were originally observed.

Impact of the BRAC Framework beyond Action Control

Action-related phenomena are an essential part of many 'building blocks of cognition'. We discuss here the mutual impact of the BRAC framework and different areas of research that are closely related to action – namely attention, memory and learning, and motivation (Figure 2). Again, many well-known effects we discuss here can be separated into feature binding and retrieval parts, and BRAC is tailored to the prime–probe structure of these phenomena.

BRAC and Attention

In many approaches to attention, feature integration and feature weighting are core processes as they are in BRAC ([63] for a recent discussion). In addition, intertrial effects in attention paradigms have led to debates about the interplay of attention and retrieval mechanisms – a debate that can be perfectly accommodated and moderated by BRAC.

Spatial orienting as in the Posner cuing task consists of a sequence of two events. A cue which carries a spatial feature (e.g., RIGHT) is bound to an orienting response (*cf* premotor theory of attention [64]) followed by a subsequent target either carrying the same spatial code (RIGHT), and thus retrieving the previously bound orienting response that facilitates target processing (in a valid trial), or carrying a different spatial code and hence does not retrieve the planned orienting response (in an invalid trial). BRAC can thus describe validity effects in spatial cuing. In addition, once the target is processed, another feature becomes available, namely whether the target episode was validly or invalidly cued. Repeating the spatial feature from the preceding target event in the cue event of the next trial will reactivate the previous target episode, including its validity feature. This invokes the 'expectancy' that the cue will also be valid or invalid, thereby increasing the benefits of an actually valid trial and decreasing the costs of an actually invalid trial. Thus, BRAC might partly explain intertrial modulations of cuing effects [65–67].

In the same vein, intertrial effects in visual search can be explained in terms of binding and retrieval: in visual search [68,69], in so-called compound search tasks [70,71] participants search for a target that could pop-out in one of two dimensions in an array of multiple distractors. Targets contain a relevant feature that must be discriminated [71]. In such tasks, in which a response-defining feature follows target selection, reaction-time benefits occur when the target-defining dimension and response-defining feature fully repeat; however, if the target-defining dimension repeats, but the response-defining feature changes, responses are slowed down [70–72]. This pattern is easily explained by response retrieval due to feature repetition. Thus, BRAC can be used to link the research on visual search and attentional orienting with research on action control.

BRAC and Memory/Learning

Given the connection between the event-file concept and episodic memory, it is important to more closely investigate the relationship between binding and short-term memory, as well as between binding and long-term memory. Although this connection may sound obvious (event-files might be considered similar to Logan's [18] instances, which represent memory entries), there are

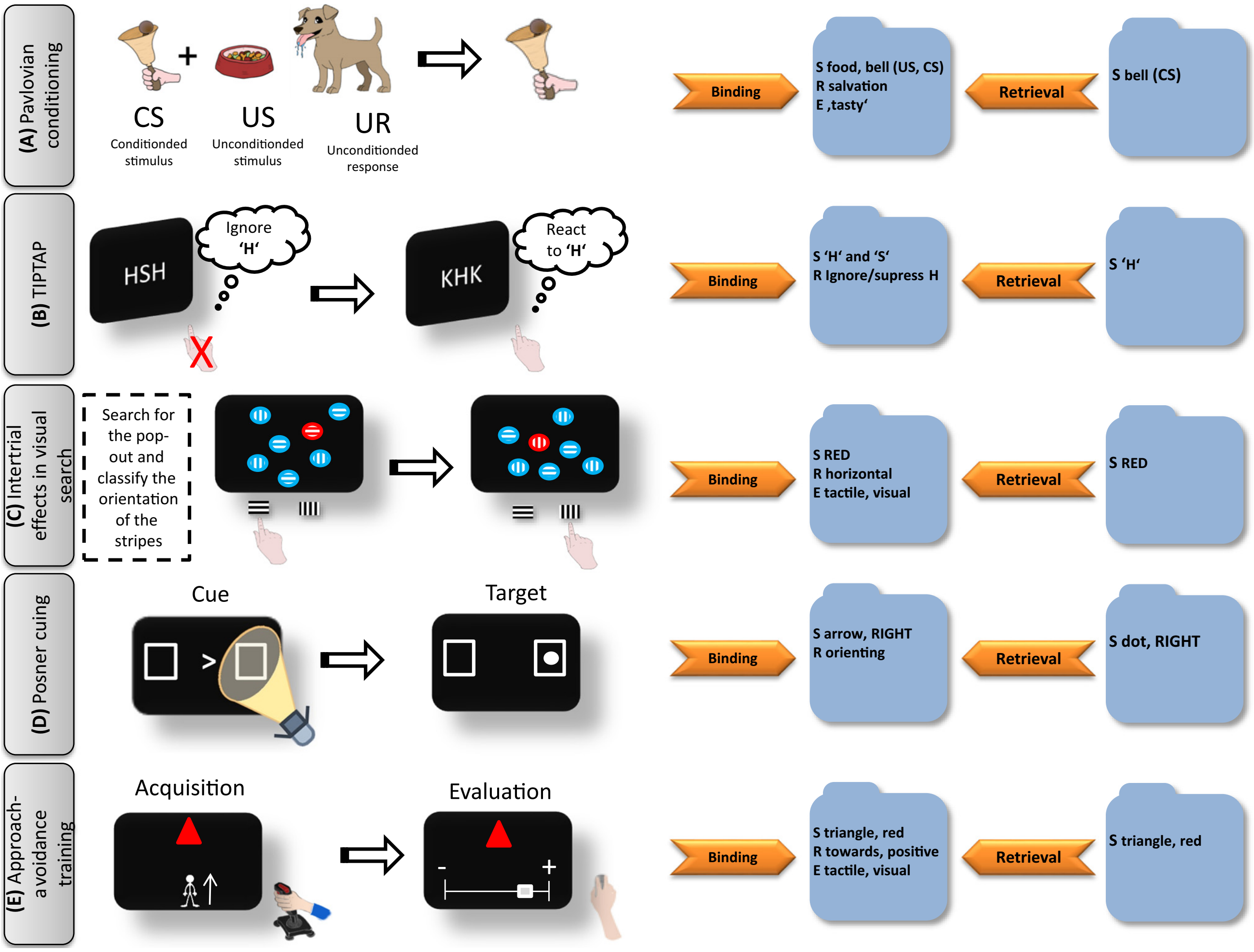

Figure 2. Applying the Binding and Retrieval in Action Control (BRAC) Framework to Phenomena beyond Action Control. Examples of action-related phenomena described by the BRAC framework from the areas of learning and memory (A,B), attention (C,D), and motivation (E). (A) In Pavlovian conditioning a response-neutral stimulus (the bell; conditioned stimulus, CS) is associated with a response-eliciting stimulus (the food; unconditioned stimulus, US) that triggers a response (the salivation; unconditioned response, UR). After several pairings, the CS triggers salivation (the conditioned response, CR) on its own. The BRAC framework assumes binding of CS, US, and UR into one event-file and retrieval of this event-file upon CS repetition. (B) Transfer-inappropriate processing/transfer-appropriate processing (TIPTAP) describes the principle that the processing mode from a previous episode is retrieved and can thereby facilitate or hinder performance depending on whether the processing mode is appropriate or inappropriate (here: 'ignore' followed by 'respond to'). BRAC can incorporate the processing mode as a response feature of an event-file and thereby describe the TIPTAP principle. (C) Intertrial effects in visual search occur when a target-defining dimension (here the color red) repeats while the response (vertical vs horizontal) changes. The BRAC framework can explain this result by assuming that the target color is bound to the response and, upon repetition, retrieves the previous event-file including the response. (D) Posner cuing denotes the finding that cues elicit validity effects (faster responses to spatially congruent targets). BRAC assumes that the spatial feature of a cue (e.g., RIGHT) is retrieved when the target appears at the same location, and hence the previous orienting response is also retrieved. (E) Approach–avoidance training changes stimulus evaluations (approach behavior makes the evaluation of a formerly neutral stimulus more positive). BRAC explains this effect as binding of affective features of the prime action (approach, +; avoidance, –) associated with a stimulus, and by repeating the stimulus the affective feature of the prime is retrieved, thus changing the evaluation of the stimulus.

findings suggesting the independence of long-term memory and binding [73,74]. Even so, memory and action control have been linked in recent approaches to action control (Box 1).

Along the same lines, BRAC raises the question whether and how both event-files and long-term memory rely on learning, for example, contingency-based learning and reward-based learning

[54,75–77]. This is particularly promising because BRAC bears a striking structural resemblance to the basic paradigm that characterizes Pavlovian conditioning. Specifically, in Pavlovian conditioning, incidentally pairing a formerly neutral stimulus (conditioned stimulus, CS) with a stimulus eliciting a response (unconditioned stimulus/unconditioned response, US/UR) endows this CS with a tendency to trigger the same response on a later occasion, even in the absence of the US [78]. Similarly, in standard binding and retrieval paradigms ([26]; also [22,24,25,54]) it has repeatedly been shown that a prime distractor activates the specific prime response when the same stimulus is presented again during a subsequent probe trial. Despite differences with regard to the behaviors that have been studied in the two paradigms, and also with regard to the designs (learning after extended practice in Pavlovian conditioning, compared to single-trial effects in the retrieval paradigm; *cf* [79]), it seems promising to investigate episodic binding and retrieval as potential contributors to Pavlovian conditioning effects [54].

Highlighting the importance of BRAC for understanding learning, recent studies demonstrate that effects of contingency learning were eliminated after controlling for effects of episodic response retrieval [76,77]. Apparently, habit acquisition and maintenance are, to a large degree, mediated by retrieving the last occurrence of the current stimulus situation and reactivating the response that was bound to it. Such a recency-based episodic retrieval account of learning [76] provides an alternative explanation for the 'law of exercise' [80] that competes with standard frequency-based explanations [81].

The relevance of episodic response-retrieval processes for explaining learning is further corroborated by a recent study that analyzed the modulating effects of affective consequences on binding and retrieval [75]. In that study, negative performance feedback after a previous response episode led to a reversed response-retrieval effect for this episode. Similar modulating effects of affective consequences on retrieval were recently reported in research on action–effect bindings [82,83]. Based on these preliminary results, we think that BRAC provides a promising perspective to explain learning effects from the domain of conditioning research (Pavlovian conditioning, operant conditioning, and even evaluative conditioning [15,84]) in terms of episodic response retrieval.

BRAC can also describe influences of transfer-inappropriate processing/transfer-appropriate processing [85] from memory research on actions. Negative priming has been explained in terms of transfer-inappropriate processing [86] in that a prime distractor is processed as 'being irrelevant', which in the case of repetition as a probe target slows down responding because an inappropriate processing mode is retrieved. BRAC can explain this finding by assuming that the processing mode is a feature of the prime event-file. If the prime event-file including the processing mode is retrieved, it can facilitate or hinder probe processing depending on the appropriateness. More generally, BRAC suggests implementing the transfer-inappropriate processing/transfer-appropriate processing principle in prime–probe designs defined as compatibility of the response-generation processes between prime and probe event-files.

BRAC and Motivation

BRAC provides a novel perspective on core phenomena in the psychology of motivation. Established theories explain motivational force by drawing on either 'liking' (evaluation, incentive value [87]) or 'wanting' (drive, desire [88]). BRAC explains how 'wanting' and 'liking' emerge and change. Because they are treated as motivational responses (approach vs avoidance [8]) that become bound to specific stimuli, they then elicit these motivational responses via episodic retrieval. Thus, approach and avoidance behavior impact on the evaluation of a (formerly neutral) stimulus ([84,89,90]; also [15]). If a stimulus is approached, the features of the action (including the affective code that is part of the action representation) and the stimulus features become integrated into an event-file, and upon repetition of the stimulus the affective features are retrieved, shifting the evaluation of the stimulus in a positive direction. With respect to BRAC, it seems important to investigate whether stimulus evaluation is changed directly after an approach or avoidance action or whether several repetitions must have occurred before affective codes from the action are transferred to a stimulus. More generally, the relation between BRAC and the research on approach and avoidance behavior is mediated by the relation between BRAC and learning/memory (see above and Outstanding Questions). BRAC further emphasizes the sequential character of many approach and avoidance training procedures that use an acquisition phase followed by a stimulus evaluation phase. In this vein, BRAC offers a new episodic retrieval perspective on motivational phenomena such as 'cue-triggered wanting' in addiction [91], or context-dependent relapse of conditioned fear after extinction-interventions [92].

Concluding Remarks

Action-control research has tried to pinpoint the sub-processes of actions and to isolate specific aspects that humans use to regulate action. The result is an abundance of detailed and often paradigm-specific findings and debates. Summarizing the rich literature on action control, we introduce a framework that is based on two core processes – feature binding and retrieval. Although many open questions remain (see Outstanding Questions), the emphasis of BRAC on disentangling influences on feature binding and retrieval as separate processes that contribute to the observed ‘binding effects’ will have a lasting effect on cognitive approaches to action. In addition, because the framework is relatively simple, it can easily be used to describe and discuss action-related phenomena from different research fields beyond action control.

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Outstanding Questions

Simply put, is binding merely learning? One of the most urgent questions concerns how action control and learning/memory interact – there is already a discussion of whether ‘binding’ refers to ‘single-trial learning’ (with *contra* [73,74] and *pro* arguments [75,76]).

A particular issue concerning the interaction of binding and learning/memory is the question of whether only the last event-file is retrieved and modulates behavior or whether all previous event-files are retrieved (perhaps to a weaker degree [42]). In this regard, the strength of the memory trace and/or the decay function of an event-file should be further analyzed [111].

What are the neural correlates of feature binding and retrieval? Neural correlates have so far been analyzed without distinguishing between the two processes. It seems that brain oscillations might actually be more suited for pinpointing binding versus retrieval at a physiological level [16] than using event-related potential (ERP) or fMRI data (because of their temporal resolution).

What are the ‘boundaries of binding’? It seems that in some paradigms measuring inhibition of return (IOR) [112] binding does not take place [113] or at least is strongly diminished [114]. It might also be argued that eye movements underlie very different constraints (e.g., a fixed time-schedule) compared with actions executed with hands or feet, and hence the BRAC framework might be exclusive for non-eye movements.

Which concrete top-down and bottom-up mechanisms impact on binding and retrieval? What are the concrete and separate effects of salience, grouping, reward, feedback, instruction, and so on for binding and retrieval?

Do binding and retrieval processes also play a role in more complex actions and action sequences? Recent studies found binding and retrieval between independently planned and executed actions [115].

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